Climatological Bulletin

Vol. 19, No. 2, October/Octobre 1985

Bulletin climatologique

Canadian Meteorological and Oceanographic Society

La Société Canadienne de Météorologie et d'Océanographie

Reconstruction of Seasonal Temperatures and Sea-level Pressures in the Hudson Bay Area back to 1700

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Original manuscript received 28 February 1985; in revised form 30 April 1985

ABSTRACT

The Hudson Bay region is rich in data useful to palaeoclimatology. Freeze-up and break-up series in the western Hudson Bay area, early meteorological measurements and tree ring series have been selected. The missing data are estimated, using the best correlated series, and from these, 23 continuous proxy series are deduced from 1700 to 1979. Sixty-seven series of seasonal temperature for the years 1925 to 1983 and 27 sea-level pressure series for the period 1953 to 1983 are produced. Temperature and presure fields are reconstructed on a seasonal basis from these proxy series using the standard transfer function. A relationship between principal components of the temperature network and the proxy series is developed for the 1925-1979 interval and extrapolated back to 1700. Temperature is deduced for six stations representative of the meteorological network. Verification tests are significant mainly for high frequencies. The trends are better estimated by an analogue method. Both kinds of reconstruction are combined and yield an improvement in results. The relationship between temperatures and pressures is used to reconstruct earlier pressure fields by the analogue method. The trend-analysis reveals that a warming occurred at the end of the 19th century. Eight classes are defined to show the main structure of the space and time variations of the temperature and pressure fields.

RESUME

La région de la Baie d'Hudson est riche en données susceptibles de fournir des informations paléoclimatiques intéressantes. Des séries de debâcle et d'embâcle de rivières de l'ouest de la Baie d'Hudson, des séries instrumentales reconstituées et sept séries dendrochronologiques ont été sélectionnées. Leurs lacunes sont comblées à l'aide des séries les mieux corrélées et finalement vingt-trois séries indirectes ("proxy data") complètes entre 1700 et 1979 en sont déduites. Soixante-sept séries de température saisonnières sont complètées entre 1925 et 1983 et vingt-sept séries de pressions entre 1953 et

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1983. Les champs thermiques et barométriques sont reconstruits sur une base saisonnière à partir de ces séries indirectes. Une première méthode est utilisée: la fonction de transfert classique. Elle consiste en le calcul d'une relation entre les composantes principales du réseau thermique et les séries indirectes sur la période 1925-1979. Celle-ci permet une extrapolation jusqu'en 1700 et un retour aux températures elles-memes via six stations représentatives du réseau. Des tests de vérification montrent le bon comportement des hautes fréquences reconstruites. Une méthode de reconstruction par les plus proches analogues est alors utilisée avec un accent particulier sur les basses fréquences. Les deux types de reconstructions sont fondues, ce qui améliore nettement les résultats. Un lien est trouvé entre champ thermique et champ barometrique. Celui-ci est utilisé pour reconstruire les pressions en six stations également par la méthode des analogues. Les tendances des reconstructions sont finalement analysées, ce qui met en évidence un réchauffement à partir de la fin du 19ième siècle. Huit classes de température sont définies montrant les principales structures des variations spatiales et temporelles des champs thermique et barométrique.

1. INTRODUCTION

There are many areas of the world and many periods of history for which no climatic data exist. It is common now to use proxy data to substitute for these gaps. Dendroclimatology provides proxy records which are continuous and reliable. These are based on ring widths and wood densities for typical tree species. Dense networks of such data are now becoming available. As well, historical archives provide much interesting information including early instrumental observations, weather diaries and descriptive chronicles of regional human activities (Catchpole, 1980). While many of these historical data have gaps and other irregularities, they can be easily identified with specific climatic parameters. Fritts, Le Roy Ladurie and Lamb (see reviews in Fritts (1976), Le Roy Ladurie (1967) and Lamb (1977)) have performed a pioneer work in this field.

The variety of historical archives of the Hudson's Bay Company pertaining to the Hudson Bay area of Canada has given to the science a source of information unique in North America. After the important study of freeze-up and break-up of MacKay and Mackay (1965), a method called "Content Analysis", enabling the quantification of these descriptive accounts was developed. Several recent papers concerning this rich collection of data have been published: Moodie and Catchpole, 1976, Moodie, 1977, Moodie and Catchpole, 1975, Catchpole and Ball, 1981, Rannie, 1983. These apply particularly to freeze-up and break-up events of different rivers emptying into Hudson Bay. These 18th and 19th century instrumental data have been checked and quality-controlled by Ball and Kingsley (1984) and Wilson (1982, 1983) for, respectively, the southwest side and the east side of Hudson Bay. Using other sources, Hillaire-Marcel *et al*, (1981) have reconstructed climatological series back to 1840 for several cities in southern Canada.

Snow geese migrations were proposed by Ball (1983) as a means of reconstructing southerly winds for northern Manitoba. Some correlations are clear but problems arise because of possible mistaken identity or amalgamation of species by the Hudson's Bay Company observers (Davies, personal communication), and also because of the higher influence of weather conditions in southern Manitoba rather than in northern Manitoba.

Tree-ring indices are presented in Cropper and Fritts (1981) for Nouveau Québec and Labrador, by Parker *et al* (1981) and Payette *et al* (1984) for the eastern coast of Hudson Bay, and by Hansell *et al* (1984) for the western coast of Hudson Bay.

A first linkage between the biophysical and historical kinds of proxy data was attempted by Jacoby and Ulan (1982) who found a relationship between freeze-up dates of the Churchill River and tree-ring series. The reconstruction of these dates does not show any trend, which is contrary to our own reconstructions as will be demonstrated later.

The aim of this paper is to use systematically both kinds of proxy data for producing reliable climatic series. The amalgamation of the reliable but discontinuous historical series with the continuous, widespread, but not always perfectly understood tree-ring series, is conceptually a synergistic tool for paleoclimatological research.

First, a statistical method, the transfer function, is employed. Introduced by Imbrie and Kipp (1971) for planktonic foraminifera, and improved by Fritts *et al* (1971) and Blasing (1978) for tree-rings, this method is based on a calibration of a regression between recent climatic series and tree-ring series and the extrapolation of the climatic series using the corresponding tree-ring data. The reconstructions will be improved here by the analogue method suggested by Alt (1983).

2. PROXY DATA

The first group of data which is taken from Moodie and Catchpole (1975) consists of freeze-up and break-up dates of rivers entering the western shore of Hudson and James Bays. Several categories have been defined by the authors for coding and three are used here: first freeze-up (cat. 1), complete freeze-up (cat. 3), first break-up (cat. 5). Six locations are used: (i) Churchill Factory 1 (1718-1739 and 1783-1866); (ii) Churchill Factory 2 (1740-1782); (iii) York Factory 1 (1714-1791); (iv) York Factory 2 (1791-1851); (v) Fort Albany (1721-1867); (vi) Moose Factory (1736-1871). The Churchill and Moosonee series have been extended to the modern period using recent data (Allen, 1977). Locations are given in Figure 1.

A second group of data is provided by Rannie (1983) for the Red River at Winnipeg (1798-1981): (i) freeze-up dates from October 1; (ii) break-up dates from March 1.

Ball and Kingsley (1984) provide monthly temperature data for

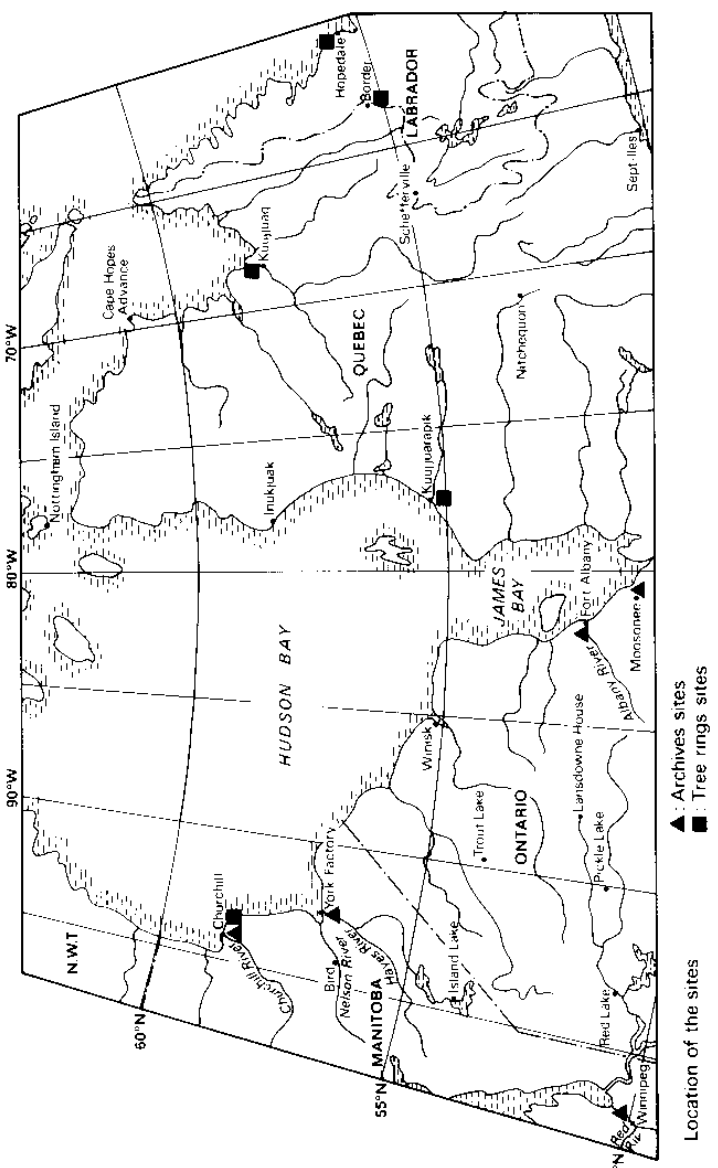


FIGURE 1. Location of the sites

York Factory (1774-1910) and Churchill Factory (1768-1769 / 1811-1858). The York Factory series are the most numerous, but the Churchill data can be connected to recent observations (1932-1983). These two monthly series have been transformed into eight seasonal series: winter (DJF), spring (MAM), summer (JJA) and autumn (SON).

Seven tree-ring series are added (Figure 1). Three are taken from Cropper and Fritts (1981): (i) white spruce ring width indices from Nain, Labrador, 1769-1973; (ii) white spruce ring width indices from Border Beacon, Labrador, 1660-1976; (iii) larch ring width indices from Fort Chimo (now Kuujjuaq), Quebec, 1650-1974. Also, two are taken from Parker *et al* (1981): Cri Lake, Quebec (near Poste-de-la-Baleine, now Kuujjuarapik) -ring width and maximum density indices. Finally, chronologies developed by P. Scott and collaborators (Hansell, 1984) in the Churchill region (Manitoba) are used: (i) open forest ring width indices for trees older than 160 years, 1691-1982; (ii) forest-tundra ring width indices, 1663-1982.

Figure 1 presents the location of the different series and, in Table 1, the identifying information for these 35 series and the most significant elements of their correlation matrix are shown.

All of these series are affected by considerable missing data, but Table 1 shows that some are satisfactorally correlated anyway. It is thus possible to estimate much of these missing data in the following way. The correlation matrix of the 35 series is computed element by element on the maximum number of observations available for each pair. The eigenvectors and eigenvalues are then computed. The missing data are replaced, after scaling, by the corresponding observation of the most correlated series, if it exists. If it does not, the next most highly correlated variable is used. This allows for deduction of the amplitudes or time variations of the principal components. Only the first 14 principal components seem to be useful to reproduce, with a small account of noise, the raw data by inverse transformation; more details are given in Guiot (1985b - in press). Thus, 35 series, complete for the period 1700-1979, are constructed. The quality of the estimation of missing data is verified by the comparison of estimated and actual values when they are available. The correlations calculated in this way range between 0.70 and 0.92, except one (for CHSP: 0.40), which are highly significant.

Further verification of the quality of the estimated data is given by computing correlations between series representing similar climatic factors (Table 2). These indicate very good results. In order to minimize local factors, the 28 historical series are merged into these 15: The three categories for Churchill 1 and 2 are reduced to 3 series (CHU1, CHU3, CHU5); same for York (YOR1, YOR3, YOR5); Albany and Moosonee are condensed into one station (MOO1, MOO3, MOO5); the two river ice series in Winnipeg, WINB and WINF are kept integrally; and the temperatures for Churchill and York are averaged (CYWI, CYSP, CYSU, CYAU). The annual mean is denoted by CYAN. These 16 series and the 7 series of tree-ring ones are shown as Figure 2a to 2d. Figure 2a also

TABLE 1 The proxy series and the most significant correlations (number of degrees of freedom).

name		label	correlation 1		correlation 2	
Churchill 1	cat 1	CH11	CH21	0.94 (5)	CHAU	0.67 (24)
	cat 3	CH13	CH23	0.84 (54)	YO13	0.45 (54)
	cat 5	CH15	CH25	0.88 (85)	YTSP	–0.47 (19)
Churchill 2	cat 1	CH21	CH11	0.94 (5)	YTAU	0.85 (5)
	cat 3	CH23	CH13	0.84 (54)	YTAU	0.66 (8)
	cat 5	CH25	CH15	0.88 (85)	YTSP	–0.51 (27)
York 1	cat 1	YO11	MOO1	0.31 (51)	CH21	0.38 (38)
	cat 3	YO13	ALB3	0.56 (71)	YTAU	0.94 (6)
	cat 5	YO15	YO25	0.94 (7)	YTSP	–0.58 (10)
York 2	cat 1	YO21	CHWI	0.68 (10)	CH23	0.64 (8)
	cat 3	YO23	MOO3	0.70 (36)	YTAU	0.68 (13)
	cat 5	YO25	YO15	0.94 (7)	MOO5	0.52 (45)
Albany	cat 1	ALB1	MOO1	0.76 (130)	YTAU	0.70 (23)
	cat 3	ALB3	MOO3	0.65 (115)	ALB1	0.65 (141)
	cat 5	ALB5	MOO5	0.86 (130)	YO25	0.49 (45)
Moosonee	cat 1	MOO1	ALB1	0.76 (130)	YTAU	0.71 (23)
	cat 3	MOO3	ALB3	0.65 (115)	YO23	0.70 (36)
	cat 5	MOO5	ALB5	0.86 (130)	YO25	0.49 (45)
Winnipeg	freeze-up	WINF	MOO1	0.45 (54)	YTAU	0.50 (28)
	break-up	WINB	YO25	0.52 (45)	YTSP	–0.46 (29)
York temp.	winter	YTWI	WINB	–0.34 (38)	MOO5	–0.34 (31)
	spring	YTSP	WINB	–0.44 (33)	CH25	–0.48 (23)
	summer	YTSU	CHSU	0.89 (4)	YTWI	–0.34 (23)
	autumn	YTAU	YO13	0.94 (6)	MOO1	0.71 (23
Churchill	winter	CHWI	YO25	–0.52 (10	YTSP	–0.62 (6)
	spring	CHSP	YO25	–0.74 (9)	CHSU	0.45 (57)
	summer	CHSU	YO23	0.65 (8)	YTSU	0.89 (4)
	autumn	CHAU	YO21	0.86 (8)	CH11	0.67 (24)
TREE-RING SERIES						
Border Beacon (Lab)		BEAI	NAII	0.42 (280)	CH23	–0.32 (55)
Fort Chomo (Québec)		CHII	CRII	0.32 (280)	YTSU	0.37 (42)
Lac Cri (Qué) width		CRII	CRID	0.30 (280)	CHSP	–0.28 (64)
Lac Cri (Qué) dens.		CRID	NAII	0.26 (280)	CHSU	0.25 (60)
Nain (Lab)		NAII	BEAI	0.42 (280)	CHSP	–0.31 (64)
Churchill open forest		CHOF	YO25	–0.50 (45)	CHSU	0.22 (60)
Churchill for. tundra		CHFT	YO13	–0.33 (77)	YTSU	0.40 (42)

TABLE 2. A few correlations between completed series.

variables	corr.	variables	corr.	variables	corr.
CH11-VH21	0.86	CH13-CH23	0.78	CH15-CH25	0.86
YO11-YO21	0.81	YO13-YO23	0.72	YO15-YO25	0.80
ALB1-MOO1	0.81	ALB3-MOO3	0.76	ALB5-MOO5	0.87
YOWI-CHWI	0.61	YOSP-CHSP	0.68	YOSU-CHSU	0.61
YOAU-CHAU	0.75				

a) Freeze-up and break-up dates: Churchill Factory, York Factory. (Julian Date)

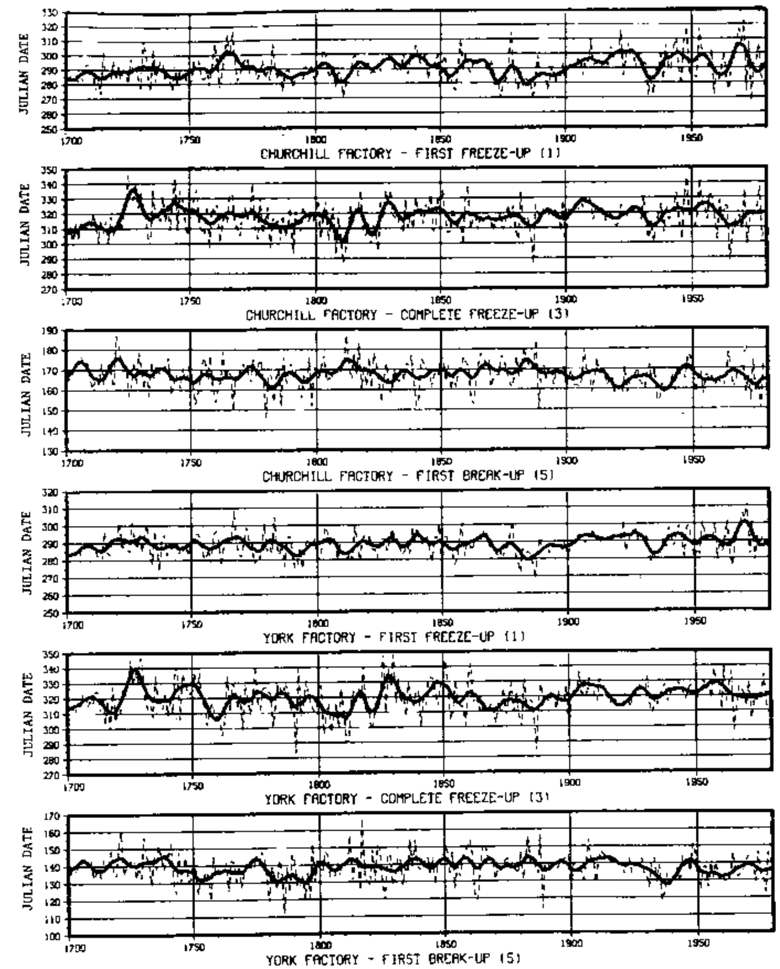
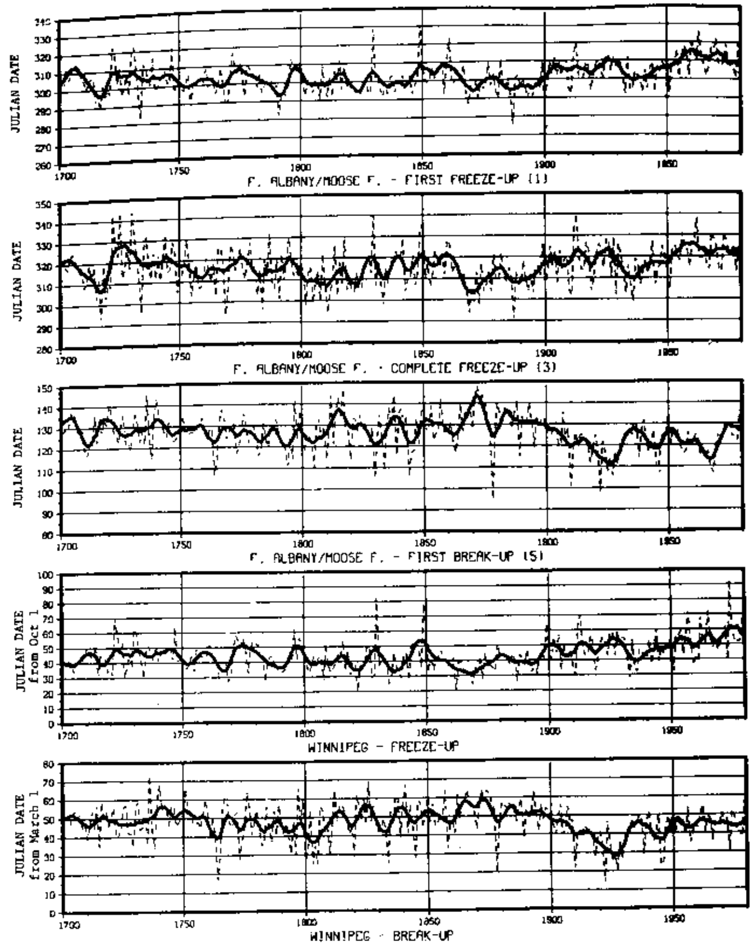
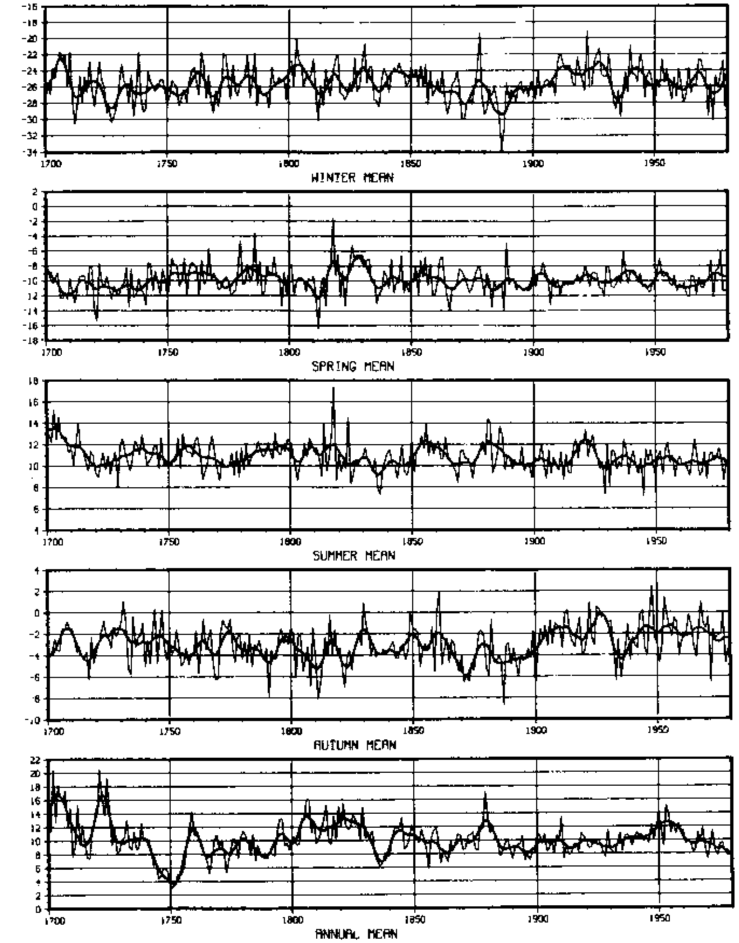


FIGURE 2. Proxy series used for the climatic reconstructions: the missing data have been estimated and some series have been averaged (see text).

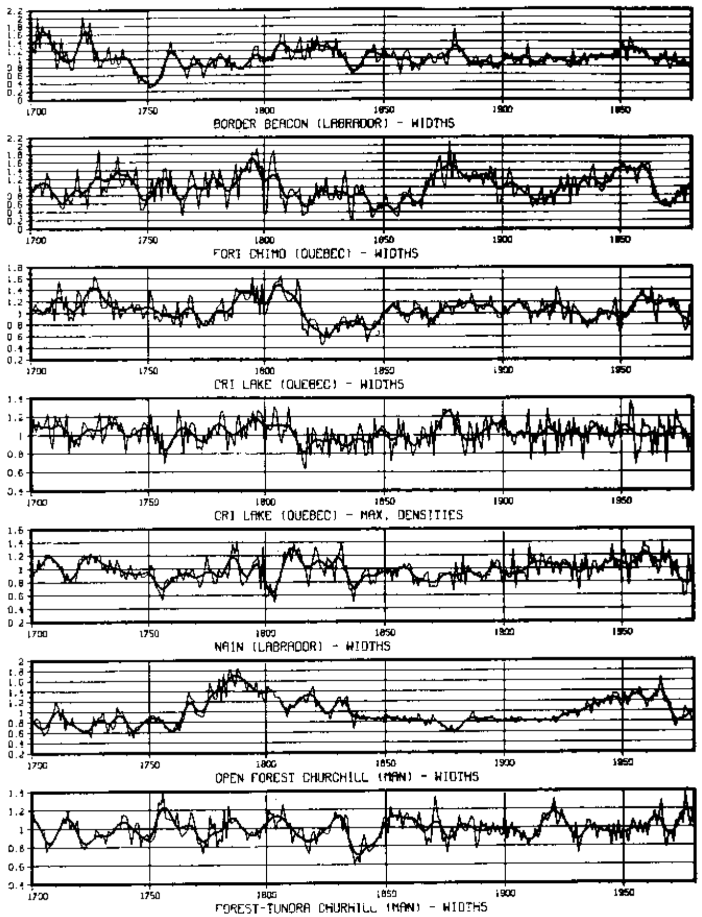
b) as in a: Fort Albany, Moose Factory. (Julian Date)



c) Temperatures at Churchill/York Factory (°C).



d) Tree-ring indices.



shows clearly that the freeze-up dates have a positive trend from 1880, contrary to the reconstruction of Jacoby and Ulan (1982). If the calibration (1741-1764) of these authors is examined, it is clear that late freeze-up during the period 1741-1750 is underestimated and early freeze-up during the period 1750-1764 is overestimated. The break-up dates show the same trend. These are related to an increase of spring and autumn temperatures. In Winnipeg the increase seems to begin 10 years earlier. The temperature series confirms the trend except for spring and summer (possibly an error in the estimations). For the tree-ring chronologies, different trends are identified and the maxima of the growth are not in the 20th century: internal plant processes and poor removal of the tree-growth trend may cause this discrepancy between ice and tree-ring data.

3. METEOROLOGICAL DATA

Between 61°W and 105°W and between 47°N and 73°N, the meteorological network of the Atmospheric Environment Service (AES) of Canada is composed of 67 stations with long series of air temperatures and 27 with sea-level pressure (SLP) (Table 3). Although the analysis period is restricted to 1925-1983 for temperatures and 1953-1983 for SLP, the many missing data (between 10 and 50 % according to the station) may bias the results. The missing data are estimated using the corresponding data of the most correlated station.

A further check on the validity of the reconstructions is to subjectively decide whether the time / space patterns which emerge make sense from a synoptic climatology viewpoint. Recent trends of the Canadian climate are presented in Thomas (1975). A brief seasonal description of general patterns will help in the understanding of the final reconstructions.

In WINTER (DJF), low pressure often occurs over the Atlantic coast and a high pressure cell is located over the Yukon Territory. This induces a prevailing north-westerly flow. In early winter, a positive thermal anomaly (with respect to latitude) is located over the Hudson Bay eastern coast (Bryson and Hare, 1974) because of the delay in the freeze-up. Arctic air masses receive considerable heat and moisture from the Bay before reaching Quebec. The atmospheric circulation is essentially meridional. In SPRING (MAM), the main centre of the high in the west of the Bay shifts southeast and the Atlantic low pressure zone fills gradually (Hufty, 1982). The heating of the land mass in western Canada induces a strong thermal gradient from the Mackenzie River to James Bay (Bryson and Hare, 1974). The thermal anomaly over Quebec is now negative because of advection from Hudson Bay and the atmospheric circulation becomes more zonal. In SUMMER (JJA), the Arctic Front has a mean trajectory close to the tree-line (extending southeast from Churchill to Nouveau Québec through James Bay). A negative thermal anomaly is located over Hudson Bay and over northern land regions having continuous permafrost. In AUTUMN (SON), the low pressure deepens again. Hudson Bay is not frozen until year-

TABLE 3. Meteorological stations used in the study. "p" indicates the use of the pressure data and "*" the absence of the temperature data. Latitudes and longitudes are given in degrees and minutes and elevations in meters.

station		lat.	long.	elev.	station		lat.	long.	elev.
NORTH-WEST TERRITORIES									
Baker Lake	p	64.10	96.00	0	Chesterfield	p	63.20	90.43	6
Coral Harb	p	64.12	83.22	64	Ennadai Lake	p	61.08	100.55	325
Jenny Lind I.		68.39	101.44	37	Pelly Bay	p	68.26	89.46	326
Sheppard Bay		68.49	93.26	51	Arctic Bay		73.00	85.18	11
Brevoort Isl.		63.21	64.10	371	Broughton Isl.		67.33	63.47	598
Cape Dyer	p	66.39	61.23	723	Cape Hooper		68.26	66.47	401
Clyde	p	70.27	68.33	6	Dewar Lake		68.39	71.14	518
Frobisher B.	p	63.45	68.33	34	Gladman Pt A		68.40	97.48	25
Hall Beach A	p	68.47	81.15	8	Lake Harbour		62.50	69.55	16
Longstaff B.	p	68.57	75.18	162	Mackar Inlet	p	68.18	85.41	399
Nottingham I.	p	63.07	77.56	16	Pond Inlet		72.41	77.59	4
Spence Bay	*	69.32	93.31	13					
MANITOBA									
Brochet	p	57.53	101.40	349	Churchill	p	58.45	94.04	29
Gillam		56.21	94.42	138	Norway House		53.59	97.50	219
Wabowden		54.55	98.38	233	Lynn Lake	*	56.52	101.04	371
Thompson	*	55.48	97.52	215					
ONTARIO									
Big Trout L.	p	53.50	89.52	219	Cent. Patricia		51.30	90.09	373
Ear Falls		50.38	93.13	361	Lansdowne Hous.	p	52.14	87.53	256
Pickle Lake		51.27	90.12	369	Red Lake A	p	51.04	93.49	386
Winisk		55.16	85.07	12	Cochrane		49.04	81.02	275
Earlton A		47.42	79.51	243	Fort Albany		52.13	81.40	15
Haileybury		47.27	79.38	215	Heaslip		47.48	79.50	222
Iroquois Falls		48.45	80.40	259	Island Falls		49.35	81.22	218
Kapuskasing	p	49.25	82.26	218	Kapuskasing A		49.25	82.28	226
Kirkland L.		48.09	80.02	320	Montréal River		47.07	79.29	183
Moosonee	p	51.16	80.39	10	New Liskeard		47.30	79.40	194
Smoky Falls		50.04	82.10	183	Timmins	p	48.30	81.20	335
Wawaitin		48.21	81.24	271					
QUEBEC									
Abitibi Post		48.43	79.22	259	Amos	p	48.34	78.07	305
Chapais		49.47	74.52	402	Chapais 2		49.47	74.52	396
Chibougamau		49.55	74.22	378	Fort George		53.50	79.00	7
La Ferme		48.35	78.10	320	La Sarre		48.48	79.12	274
Mistassini P.		50.30	73.55	383	Nitchequon	p	53.12	70.54	515
Senneterre		48.24	77.15	316	Val d'Or	p	48.04	77.47	337
Inukjuak A	p	58.27	78.07	20	Kuujjuarapik	p	55.17	77.46	14
C. Hopes Adv.		61.05	69.33	73	Kuujjuaq	p	58.06	68.25	37
Schefferville		54.48	66.49	522					

end, thus a positive thermal anomaly is induced. The Arctic Front is forced to a more southerly position until the end of December (Bryson and Hare, 1974). The late season is more homogeneous, with fewer local anomalies.

The 67 temperature and the 27 SLP series can be reduced to a few independent variables representing the basic structure of the meteorological networks using principal components (PC) analysis.

For each season, the (67x67) correlation matrix of the temperatures is transformed into eigenvalues and eigenvectors. The eigenvectors are in fact the components and the eigenvalues, in decreasing order, are the proportions of variance explained. The first four PC's explain approximatively 90% of the total variance for each season, except for the summer case where this is reduced to 82.5% (probably due to a larger variance concentrated in the smaller scales). The structure of the PC matrix is similar for the four seasons, while the relative importance of the components varies.

The first PC is called "facteur de taille" (Benzécri, 1973). This means that it represents the common variations of the network, when all correlations are positive (inducing same sign projections of the stations over this first PC). It is maximum for autumn, the most thermally homogeneous season. The second PC has a north-south gradient, the third has a pole in the east and the fourth in the west. The north-south contrast is maximum during Summer because of the Arctic Front. It is evident that main features of the climate of the Hudson Bay area are shown by this preliminary analysis.

The (27x27) correlation matrix of the sea-level pressure is transformed similarly. The first four PC's together explain from 83.7 % of the variance (summer) to 94.5% (winter). Here winter results are different because of larger scales of variations, however the same north-south and east-west gradients occur. The "facteur de taille" is weak for summer and absent for autumn. For these seasons, negative correlations are present between some eastern and western stations. This seems to be related to the position of the Arctic Front: a relatively small value of the sea level pressure in the north-east is related to a more northern trajectory of the front and thus to SLP with relatively large values in the South.

4. TRANSFER FUNCTIONS

The basis of the transfer function is a regression equation which is calibrated over a recent period where meteorological and proxy data are available. Then Equation 1 is applied to ancient proxy data so that an estimate of past climate is deduced:

$$y = \sum_{i=1}^{m} a_i x_i \tag{1}$$

where y is a climatic parameter, the x_i are the m proxy variables, and the a_i are the corresponding regression coefficients. Here, the calibration period is set to 1925-1979 and the extrapolation is extended back to 1700. For each seasonal thermal parameter, a set of meteorological variables is defined by the first four principal components (see above) and the set of proxy data is composed of 16 historical series and 7 tree-ring series (Figure 2a to 2d).

The summer temperature is used to illustrate the method. Seventeen regressors are selected: (i) the 7 tree-ring series for their evident relation with the summer climate; (ii) the same 7 one-year lagged series because of the possible persistence of the climate effect on growth; (iii) the historical series CYSU of summer temperature in the Chuchill/York region; and (iv) the Winnipeg ice condition series, WINB and WINF, in order to introduce southern variables.

The PC's of these 17 regressors are computed. Thirteen are kept, using the PVP criterion (ie. the PC with a cumulative eigenvalues product larger than 1: Guiot, 1985a). A canonical analysis between these 13 PC's and the 4 climatic PC's is performed and an inverse transform enables one to deduce the regression coefficients between the four PC's and the 17 regressors (Blasing, 1978). The results (Table 4) show that the first PC has the best fit (R^2=0.67), and as it explains the largest part of the variance of the network (41.5%), it can be said that the main characteristic of the summer temperature is well restored. Table 4 also shows that the tree-ring series are best related to the summer temperature.

The next step is the application of the regression coefficients to the whole proxy series (1700-1979). This gives an extrapolation of the thermal PC which must be retransformed to the original series. Arbitrarily, six stations are selected to represent the network and the associated proxy series: (i) Churchill, northern Manitoba; (ii) Red Lake, western Ontario; (iii) Moosonee, northern Ontario; (iv) Kuujjuarapik, central Quebec; (v) Kuujjuaq, northern Quebec; (vi) Nottingham Island, southern NWT. Table 5 shows the loading factors of the six stations on the four PC's. These loading factors, are, in fact, the weighted averages (in inverse function of the distance) of the loading factors of the neighbouring stations, used to improve the regional representativeness. They specify the retransformation back to the selected stations. The goodness of fit can be checked for 1925-1973 by the curves presented in Figure 3c: the worst disagreeements are found for Kuujjuarapik, but generally, the fit appears good.

It is necessary to check the stability of the reconstructions by using series starting before 1925. Raw data (before estimating the missing data) are used. First, the correlations between the reconstructions and the actual values for the six stations are given by Figure 4. These correlations (their average is 0.54), with degrees of freedom ranging from 30 to 40, are all significant at the 0.01-level, except for Nottingham (R=0.24). Nevertheless the reconstruction for Nottingham Island is significantly correlated with the actual values of Churchill (R=0.61), but since there are no available proxy data at this site, further explanations of its climatic peculiarities are not offered. For an independent verifi-

TABLE 4. Standardised regression coefficients (multiplied by 10) of the 4 PC versus the proxy variables for the 4 seasons.

variable	time	WINTER 1 2 3 4	SPRING 1 2 3 4	SUMMER 1 2 3 4	AUTUMN 1 2 3 4
Churchill 1	t				-1 -2 -1 -0
Churchill 3	t				-1 +1 +2 +1
Churchill 5	t	-1 +1 +0 +1	+0 +0 -0 -1		
York 1	t				-1 -0 +1 -0
York 3	t				+0 +3 +1 +2
York 5	t	+0 +2 -0 -0	-1 -1 -0 -1		
Moosonee 1	t				-3 +1 -2 -2
Moosonee 3	t				-1 -1 -1 +1
Moosonee 5	t	+0 +1 -0 -1	+0 +0 +2 -2		
Winnipeg fr.	t			+2 +0 +0 +2	+2 +3 +1 +0
Winnipeg br.	t	-3 -1 -2 -0	+2 +0 +3 -3	+2 -3 -1 -2	
Ch/York Win.	t	-7 -3 +0 -4			
Ch/York Spr.	t		-6 +2 -1 -6		
Ch/York Sum.	t			-3 -1 -0 -2	
Ch/York Aut.	t				-2 -0 +0 +0
Bord. Beacon	t	-0 +5 -1 +2	+0 -3 -2 +0	+1 -1 -2 +2	+0 -1 +0 +1
Fort Chimo	t	+0 -1 +0 -1	-0 +3 +1 +2	-2 -0 -1 +2	+0 +0 +2 -1
Cri L. RW.	t	-0 +1 -2 -0	-1 -2 +1 -0	-3 -3 +2 -1	-1 +1 -2 +1
Cri L. dens.	t	-0 +3 +2 -1	-1 +1 +2 +0	-3 -3 +2 +0	-2 -3 -3 +3
Nain	t	+3 -2 +2 -2	+3 -2 +0 -1	+3 -0 -0 +1	+2 +2 -0 +0
Chur. O.F.	t	-2 -1 -0 +2	-0 +0 +1 +2	+0 -0 -0 -2	-1 -0 -0 -1
Chur. F.T.	t	+3 -1 +2 -2	+1 -2 +2 -1	+3 -0 +1 -1	+3 -0 -0 +3
Bord. Beacon	t+1		+2 -1 +2 +0	-0 -1 -1 +0	+2 +2 +1 -0
Fort Chimo	t+1		-2 +0 +1 +3	-0 +1 -0 +1	-3 -1 -2 -2
Cri L. RW.	t+1		-2 -1 +3 -2	+2 +0 +3 +2	+0 +1 -3 -1
Cri L. dens.	t+1		+2 +1 -0 -2	-1 +1 -0 -1	-0 +1 +2 -1
Nain	t+1		-0 +1 +1 -1	+4+0 +0 +0	+1 -2 -2 +2
Chur. O.F.	t+1		-1 +1 +0 +0	-0 -2 -1 -0	-2 -1 -1 -0
Chur. F.T.	t+1		+1 -2 +0 -0	+1 -3 +1 +1	+1 +2 -0 +2
Churchill 1	t-1	+1 +0 -0 -1			
Churchill 3	t-1	+0 +0 +1 -0			
York 1	t-1	+1 +0 -1 -1			
York 3	t-1	-2 -1 +2 +3			
Moosonee 1	t-1	-1 -0 -2 +3			
Moosonee 3	t-1	-1 -1 -2 -2			
Winnipeg fr.	t-1	+1 +1 -0 -2			
determ. coeff.		65 37 44 43	57 34 53 59	67 49 42 27	72 46 53 39
F-value		5. 2. 2. 2.	3. 1. 3. 4.	6. 3. 2. 1.	6. 2. 3. 2.

FIGURE 2a) Winter Temperature

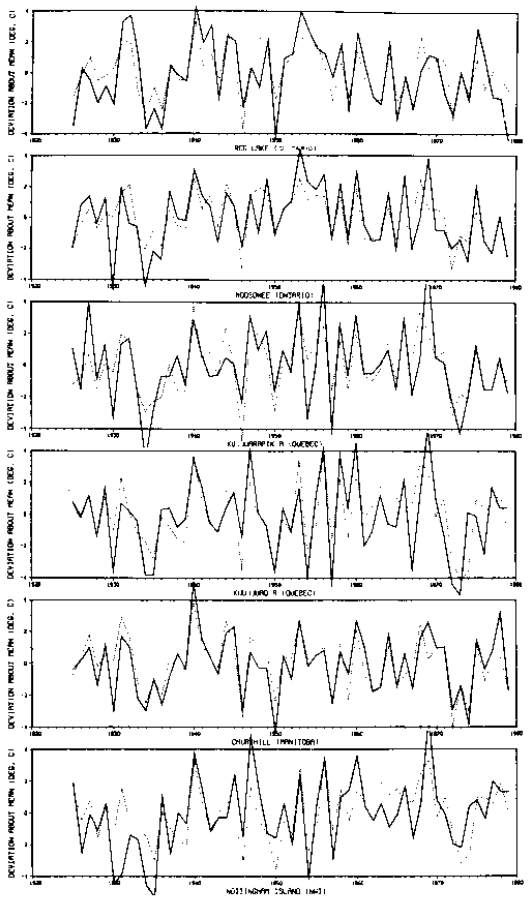


FIGURE 3. Calibration of the seasonal temperature in six stations: the dotted lines are the estimates and the undotted lines are the actual observations. Solid lines represent the filtered series (the cut-off period of the filter is 7 years).

FIGURE 2b) Spring Temperature

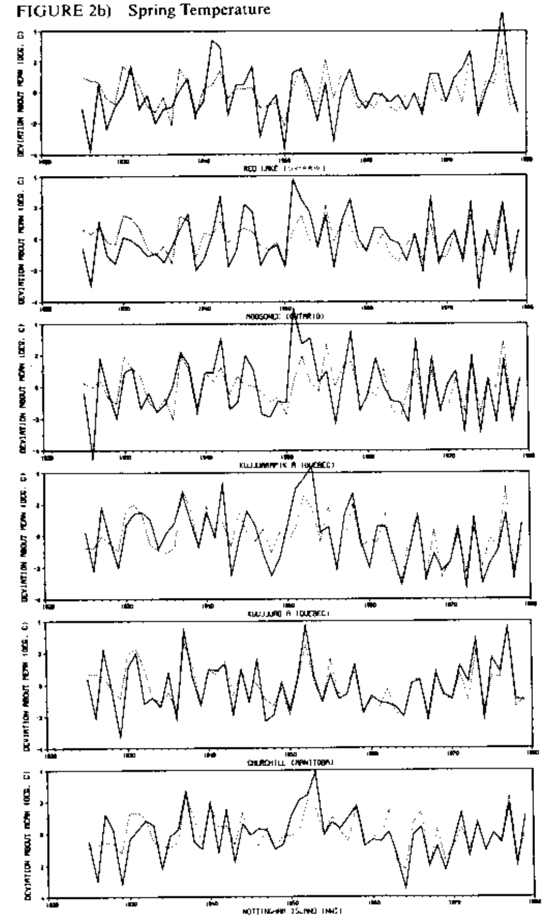


FIGURE 2c) Summer Temperature

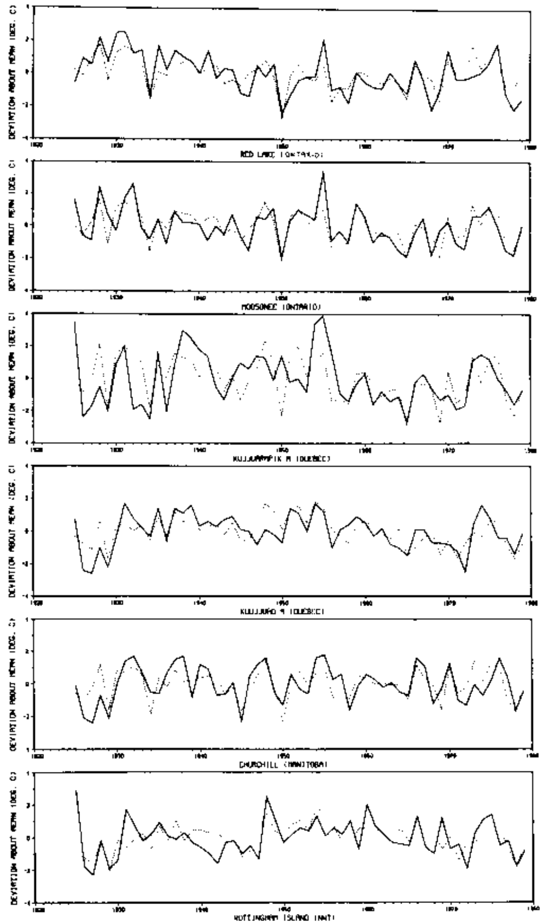


FIGURE 2d) Autumn Temperature

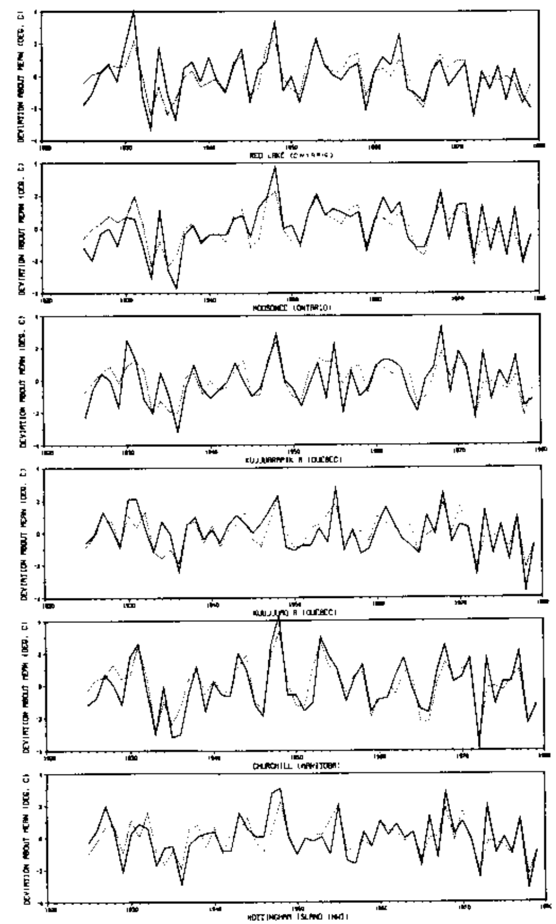


TABLE 5 Loading factors of the 6 stations vs. the 4 PC for 4 seasons; these are the eigenvectors (averaged on a regional basis) multiplied by the standard deviation of the corresponding PC and by this of the corresponding station, so that the reconstructions are in °C.

		Red L.	Moos.	Kuujjar.	Kujjuaq	Church.	Nottingham
Winter:PC	1	-1.79	-1.85	-2.26	-1.79	-1.86	-1.27
	2	.90	.69	.28	-1.53	.00	-1.52
	3	.24	.23	-.57	-.77	.46	-1.27
	4	-.45	.23	.00	.26	-.46	.00
Spring:PC	1	-1.47	-1.38	-1.79	-1.58	-1.54	-1.13
	2	-.74	-.31	-.55	.79	.00	.64
	3	-.37	-.15	.22	.59	-.39	.64
	4	-.18	.15	.00	.00	-.39	-.32
Summer:PC	1	-1.05	-1.12	-1.54	-.58	-.98	-.28
	2	.15	-.14	-.22	-.63	-.41	-.84
	3	.60	.14	-.22	-.63	.27	-.56
	4	.00	.00	.00	.25	-.41	-.28
Autumn:PC	1	-1.34	-1.38	-1.35	-1.12	-1.58	-1.08
	2	.50	.46	.15	-.42	.20	-.62
	3	.17	.00	-.15	-.28	.60	-.31
	4	-.17	-.15	.15	.28	.20	.31

cation, it is necessary. sometimes to use distant stations. Nevertheless, the intercorrelations are sufficiently high so that large scale climatic variations can be analyzed. Data from three meteorological stations are available: (i) Fort Hope (Ontario), with 17 years of valid observation in the 1891-1930 interval; (ii) Moose Factory (Ontario), with 48 observations in the 1877-1938 interval; (iii) York Factory (Manitoba), with 42 observations in the 1714-1870 interval. The first two can be used to check the reconstruction of Red Lake, the second for Moosonee and Kuujjuarapik, and the third for the others. The correlations are presented in Figure 4. Their average is, 0.42, which is close to the fit over the dependent period: the reconstructions are thus stable in spite of a relatively modest fit. A last signal check is given by computing the correlations with the longest series: (i) Norway House, Manitoba, with 38 observations between 1885 and 1968; (ii) Cochrane, Ontario, with 63 observations between 1910 and 1979; (iii) Mistassini, Québec, with 55 observations between 1885 and 1980. It is clear (Figure 4) that these are also significant (R ≅ 0.50).

The same procedure is applied to the other three seasons. As presented for summer, Table 4 shows the regression coefficients, Figure 3 shows the accuracy of the fit and Figure 4 the verification correlations. It is clear that these seasons are better reconstructed than summer. As tree-ring series are more related to summer temperature and ice condition series are more related to other seasons, this better fit demonstrates that historical series have clearer linkage with climate than tree-ring series. The correlations with actual values over the calibration interval are larger than 0.70 and close to 0.50

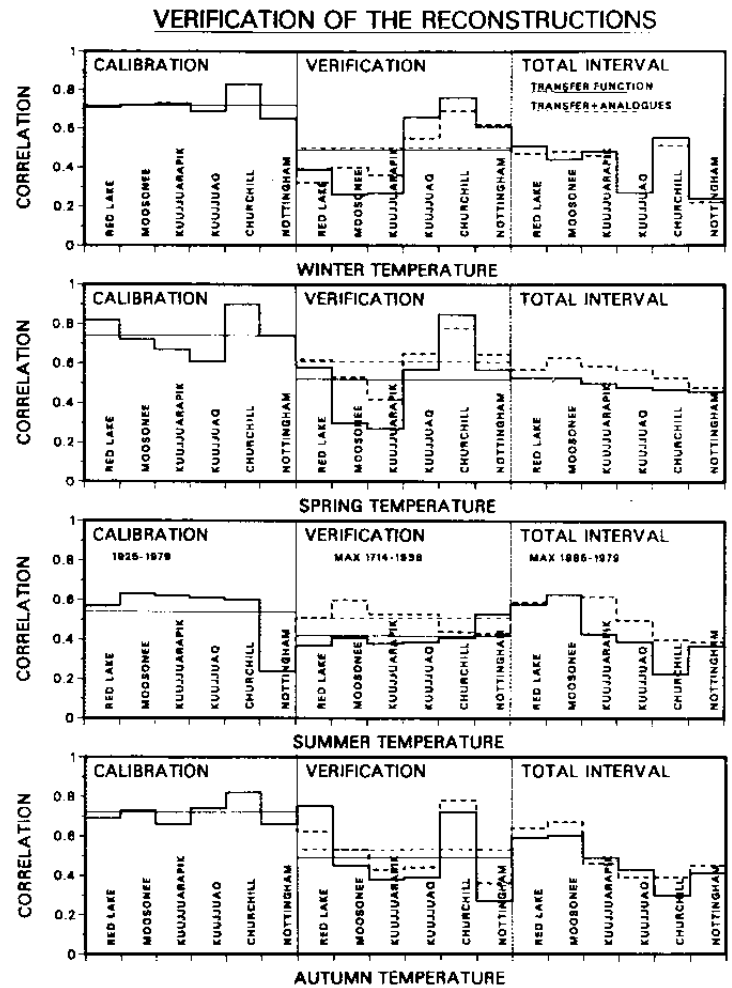


FIGURE 4. Correlation coefficients between the reconstructions and the actual observations. These are computed, over the 1925-1979 calibration interval, for the six selected stations; over various intervals extending maximum over 1714-1938, for three other stations (Fort Hope, Ont., Moose Factory, Ont., York Factory, Man.); and over various intervals extending maximum over 1885-1979, for three other stations (Norway House, Man., Cochrane, Ont., Mistassini, Qué.).

over the independent interval. Finally, six series, for four seasons, are available. Six annual series are produced by averaging the four seasons.

This kind of verification is not adequate to check the reliability of the trend, because the reference series are too short. The historical series of annual temperature, given by Ball and Kingsley (1984), will be used to verify the goodness of fit of the trend for our reconstruction of Churchill's annual temperature. Six periods are defined according to the availability of the data (Table 6). Both series are compared to their mean and the anomalies are computed for the six periods. The evident discrepancy shows that the trend is not well reproduced. This conclusion can probably be extended to other reconstructions. Some procedures for improvement will be examined below. Only the final reconstructions will be presented in Figure 5.

5. ANALOGUE METHOD

In the preceeding section, the transfer function enabled one to fit very well the interannual variations, but not the trend. Essentially, the transfer function, which extrapolates the information contained in the reference set, is dominated by the higher frequencies, which control the fitting criterion and finally the extrapolation. An alternative method is now proposed which was also used by Alt (1983), but in a qualitative way. The current data, between 1925 and 1979, are considered as a reference set which contains all possible scenarios of the climate between 1700 and 1924. So, for each year from 1700-1924, an analogue is searched for in the period 1925-1979. The selected scenario is considered as a "model" for the historic year. With this method, it is not possible to obtain a more extreme yearly climate than those which are represented in the reference set; only frequent cold years can be responsible for a colder mean climate than those included in the reference years. The results will show a posteriori that the 1925-1979 period is sufficiently exhaustive.

TABLE 6 Mean anomalies of the annual temperature (to the 1925-1979 normals) in York Factory (actual values) and in Churchill (estimates) for different periods when historical data are available. The normal at York is evaluated to -7.3°C and at Churchill to -6.7°C. The first reconstruction (FT) is given by transfer function and the second one (FT+A) is given by transfer function + analogues method.

period	no. obs	York Factory	Chur. FT	Chur. FT+A
1775-1797	10	-0.24	+0.65	-0.19
1815-1826	12	-0.04	-0.47	-0.50
1827-1832	6	+1.15	-0.15	-0.05
1838-1852	15	+0.02	+0.38	+0.10
1875-1889	15	-0.77	-0.26	-0.33
1899-1910	12	-0.13	+0.27	+0.07
1775-1910	70	-0.13	+0.07	-0.16

a) winter (°C)

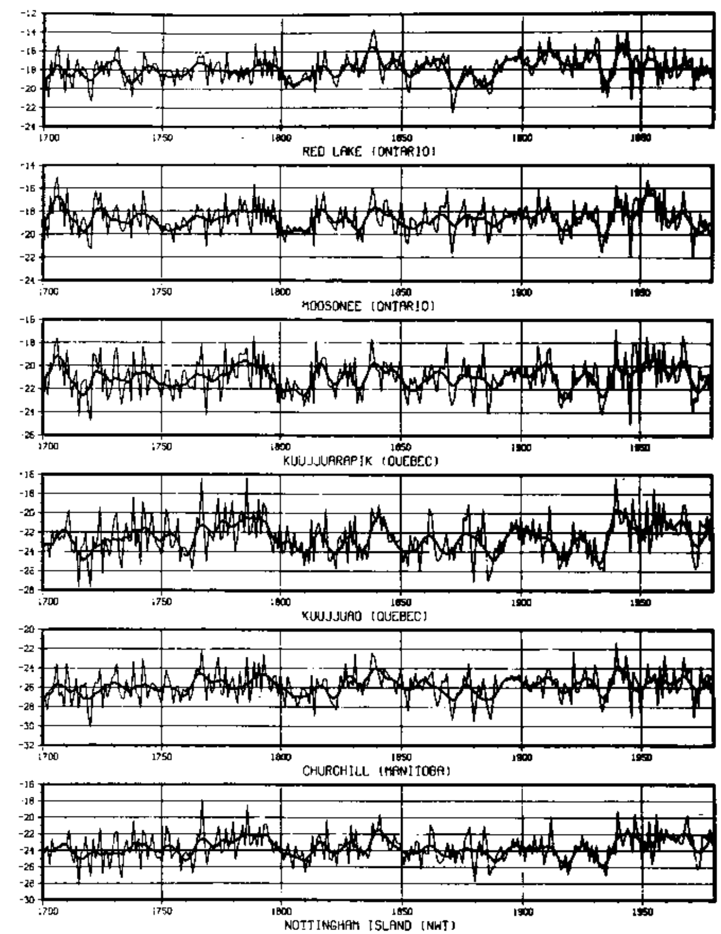
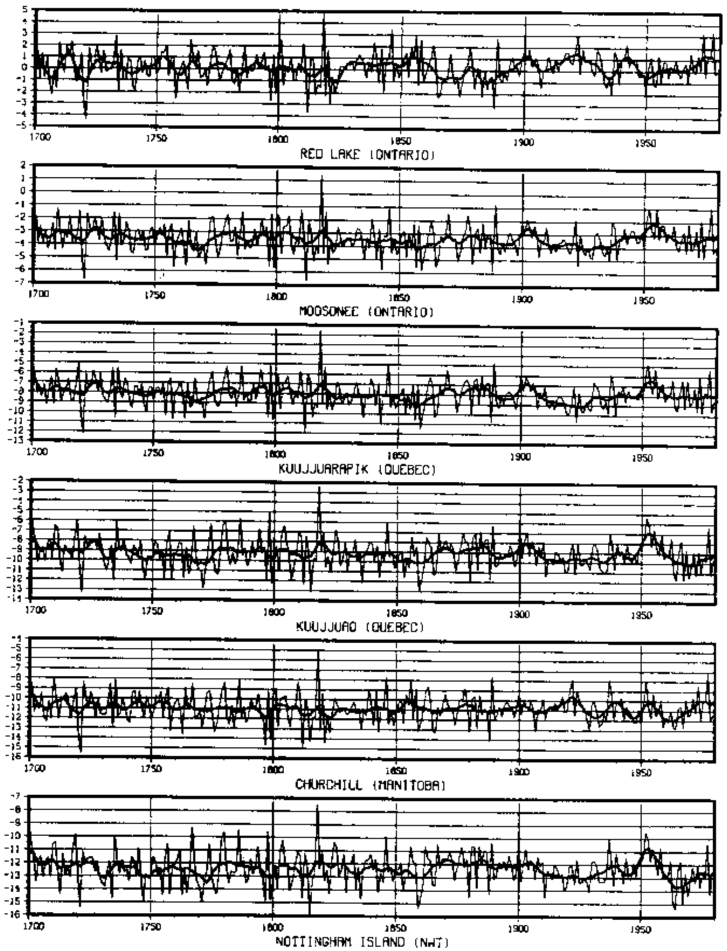
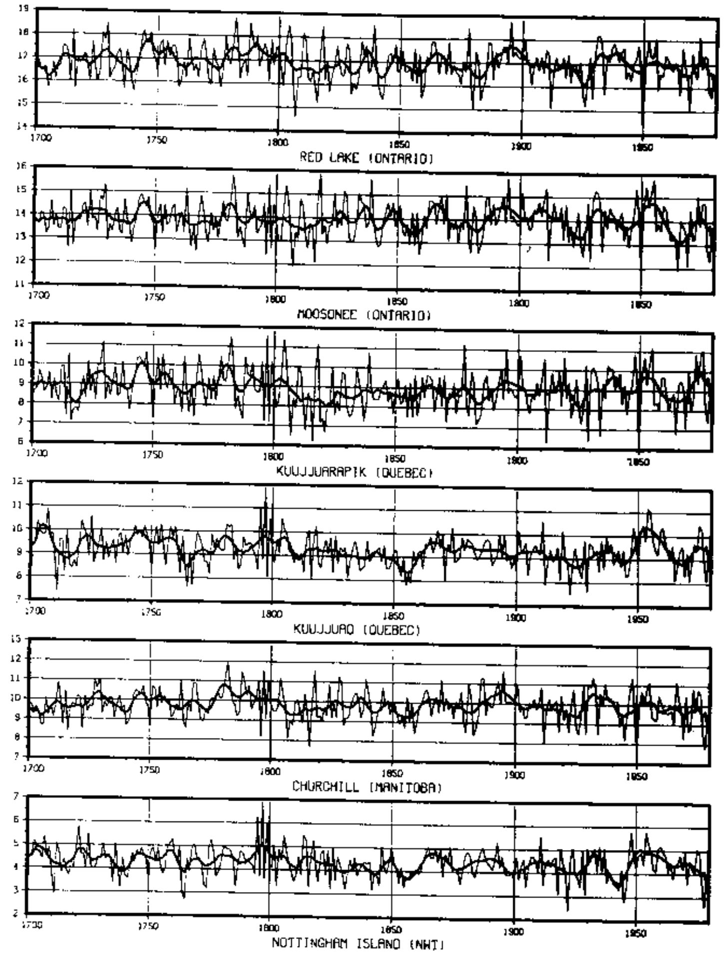


FIGURE 5. Reconstructions of the seasonal temperatures for six selected stations; the darker lines represent the temperatures smoothed by a digital filter (cut-off period = 7 years).

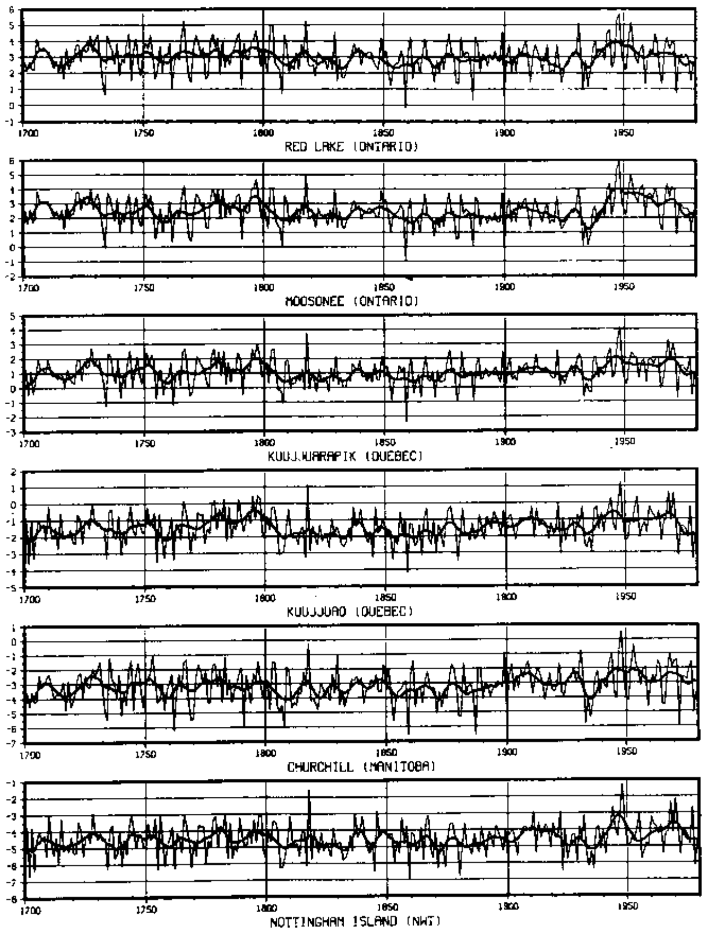
b) spring (°C)



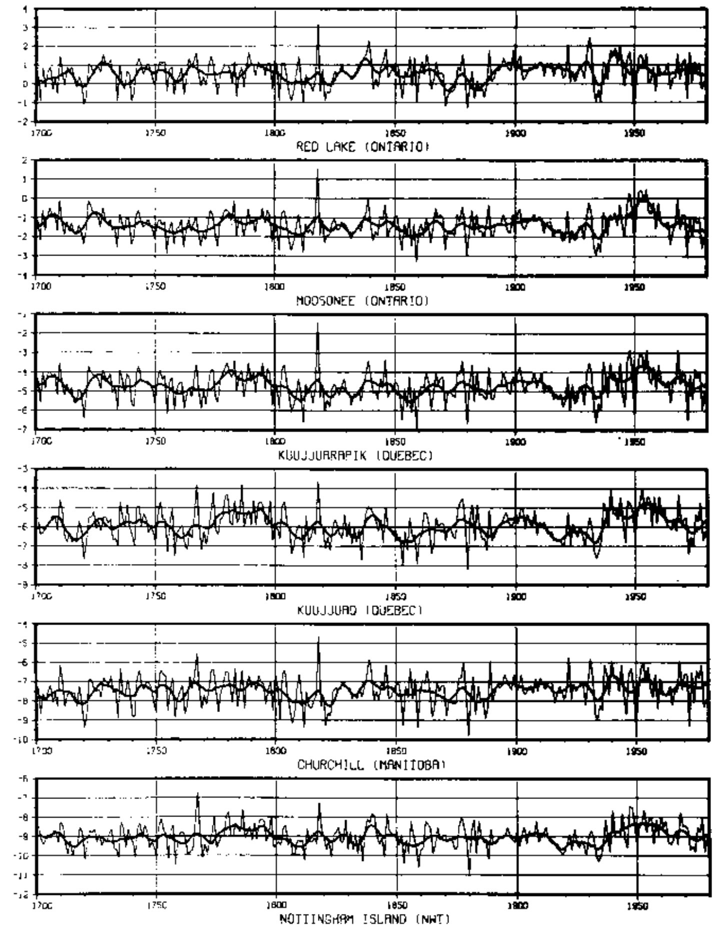
c) summer (°C)



d) autumn (°C)



e) annual (°C)



In order to achieve the best application of this method, it is necessary to carefully choose the defining criteria of the analogue. The eleven ice condition series and the seven tree-ring series have appeared exhaustive in the preceeding section. These 18 variables are transformed into 13 principal components, selected by the PVP criterion, as seen in the preceding section, in order to reduce the redundancy and the noise. Nevertheless all of these variables are not equally important in representing the temperatures of the region. Canonical analysis may be used to define the linear combination of the proxy series which is the most correlated with the temperatures.

The 4 PC's of the four seasonal temperatures are used as the dependent set, so that the complete thermal field is considered simulaneously. In order to emphasize the trend and because the tree-ring series are often autocorrelated, the 16 climatic PC's are time-filtered as follows:

$$y_t^f = 0.25\, y_{t-1} + 0.50\, y_t + 0.25\, y_{t+1} \tag{2}$$

where the index f indicates the filtering. This filter has a response of less than 50 % for frequencies larger than ¼. Finally two groups with a similar frequency behaviour are defined: (I) the 13 PC's of the 18 proxy data sets and (II) the 16 PC's of the filtered seasonal temperatures. A canonical analysis (for details see Clark, 1975) was performed on the 1925-1979 interval. The first 9 canonical axes are significant (0.05 level) according to a chi-squared criterion. These are computed, for the proxy variables, over the 1700-1979 interval. The resulting (280 × 9) matrix is used to define the analogues. These have the characteristic to best represent the temperatures. Now it is necessary to define a proximity measurement. The year k from the 1925-1979 interval is said to be the best analogue of the year i from the 1700-1924 if:

$$d(i,k) = \sum_{j=1}^{9} (x_{ij} - x_{kj})^2 \text{ is minimum} \tag{3}$$

where x_{ij} is the value of the jth canonical component for the year i. For every year i, the best analogue (k) is found and the thermal regime of year k is assigned to i, i.e. the mean temperature of the four seasons.

By using a 7-weights low-pass filter (the sâme as used for smoothing the reconstructions of Figure 5), the low frequencies of the series reconstructed by the analogue method are retained and those of the series reconstructed by the transfer function are removed. The resulting series are summed and the final reconstructions are depicted in Figure 5.

Figure 4 enables the evaluation of improvements obtained by the coupling of both methods. It is clearly better for spring and summer (mean correlation increases, respectively, from 0.52 to 0.61 and from 0.42 to 0.51), modestly better for autumn (from 0.49 to 0.53), and negligible for winter. Table 6 shows that the trend is now well reconstructed since the anomaly of the period 1775-1910 is estimated to -0.16°C, which compares favourable to the actual -0.13°C.

6. RECONSTRUCTION OF THE SEA-LEVEL PRESSURES

An initial observation is that the sea-level pressures are not independent of the temperatures (Table 7), but that the linkage is complex.

The proxy data available do not allow a direct reconstruction of the total pressure variation, but only those parts which are related to the temperature field. A regression is computed between the selected 16 PC's of the pressure field and the 30 temperature series (6 selected stations for reconstruction × 4 seasons / annual mean) over the common 1953-1983 interval. The regression coefficients are then applied to the reconstructed temperature series from 1700 to 1979. A (280 × 16) matrix is so developed, that will define the analogues. Finally the seasonal SLP series for the 6 selected stations are reconstructed by using relationship (2) with this (280 × 16) matrix (Figure 6). Table 8 shows that SLP at Thompson (THOM) and Nottingham Island (NOTT) provide the most stable reconstructions and the best reconstructed seasons are winter and autumn. Nevertheless, this is not a proof of validity, because the correlations between both fields are not perfect.

A second possibility of verification lies in a comparison with the reconstructions by Fritts *et al* (1971) for North America, Atlantic and Pacific Oceans. For Hudson Bay, these authors found winter anomalies of -2 mb in 1731-1735, 0 to 2 mb in 1791-1795 and 1811-1815 and finally 2 to 6 mb in 1890. Figure 6 confirms all except for the 1811-1815 series. The end of the 19th century and the beginning of the 20th are characterized by annual mean high pressures, while the 80 previous years are designated by low pressures, which appear also in the reconstructions of Fritts *et al.* This is encouraging and will be discussed below.

7. TREND ANALYSIS

The 1700-1979 interval can be divided into eight 35-year intervals, which is close to the standard normal period for climatological data (the standard number 30 is not chosen because it does not divide 280). The reconstructed temperatures and SLP are averaged for each 35-year interval by steps of 17.5 years.

In winter (Figure 7a), two temperature maxima appear 1) at the end of the 18th century and 2) the middle 20th century in the East, and,

TABLE 7 Multiple correlations between the PC of the SLP and those of the temperature.

PC SLP	Winter	Spring	Summer	Autumn
1	0.76	0.85	0.75	0.79
2	0.75	0.88	0.85	0.82
3	0.88	0.78	0.75	0.84
4	0.75	0.82	0.72	0.84
total	0.77	0.85	0.79	0.81

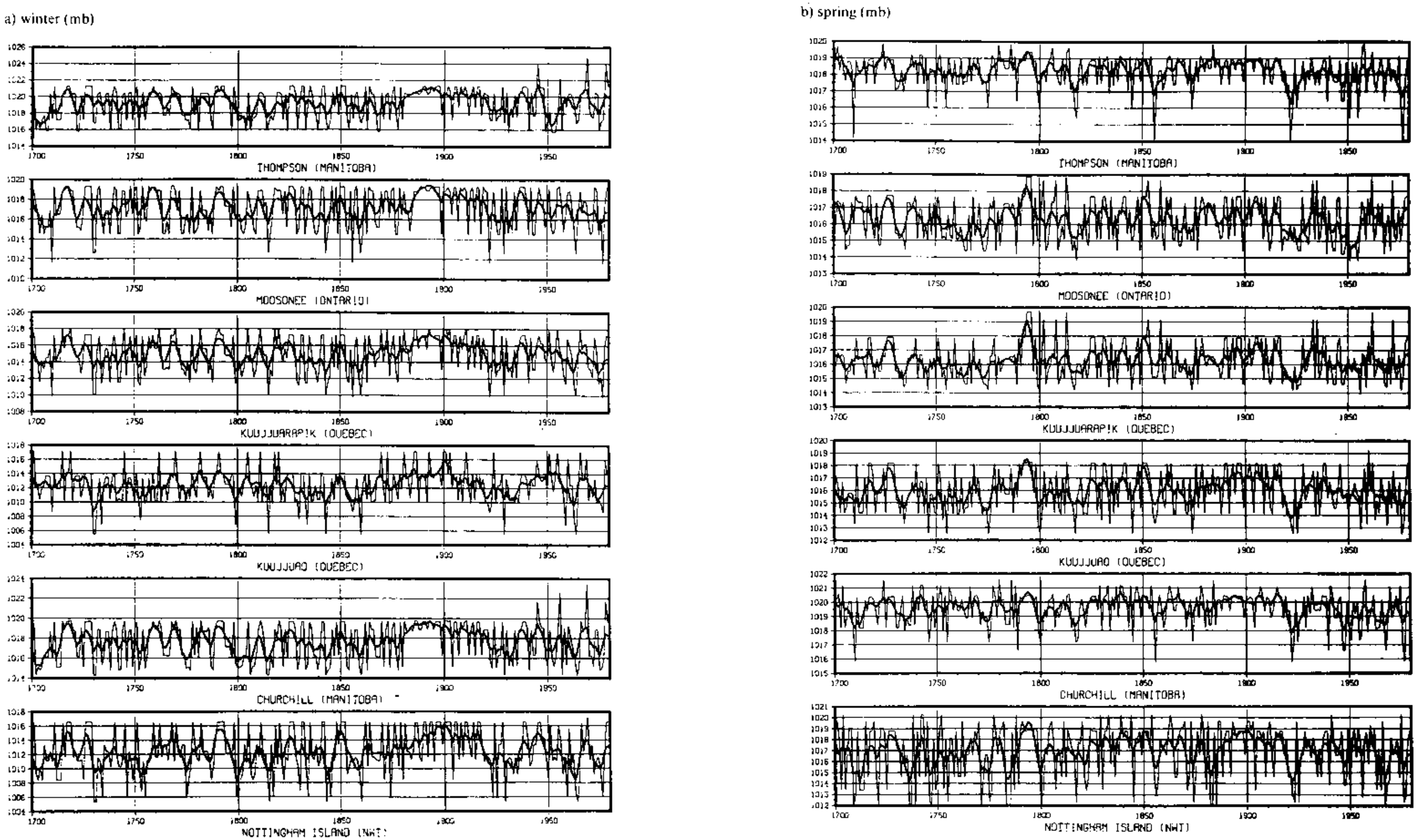
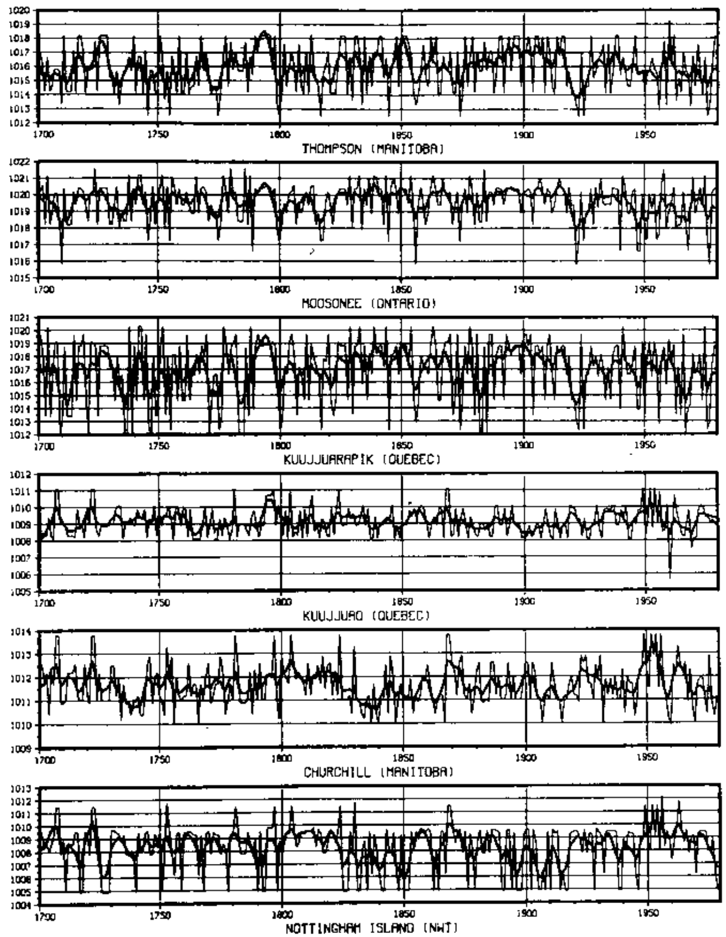
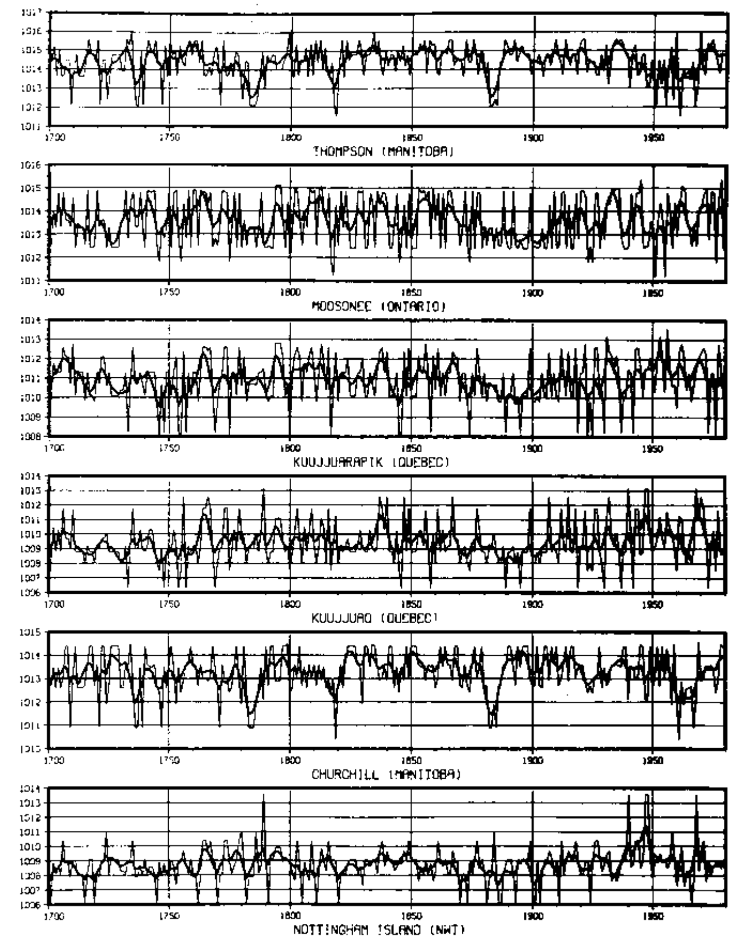


FIGURE 6. Reconstructions of the seasonal sea-level pressures for six selected stations; the darker lines represent the SLP smoothed by a digital filter (cut-off period = 7 years).

c) summer (mb)



d) autumn (mb)



e) annual (mb)

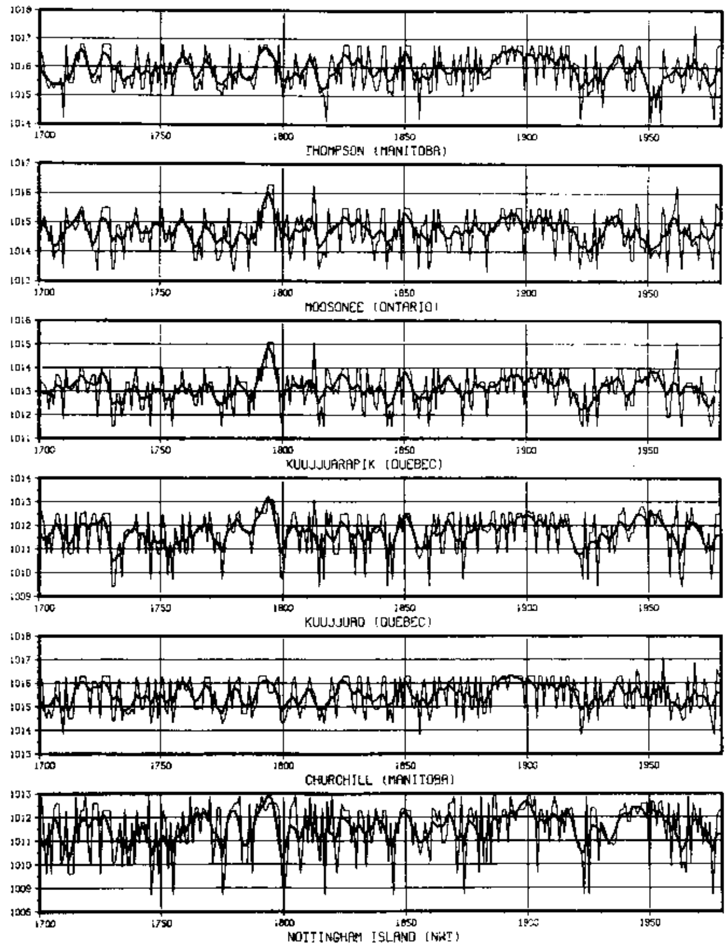


TABLE 8 Verification of the stability of the correlation between reconstructed SLP and actual temperatures. The stations are represented by the first four letters except KUUJ = Kuujjuarapik, KUUA = Kuujjuaq, MOOF = Moose Factory. ndf = number of degrees of freedom. Only the parameters with at least a significant correlation are presented.

actual P/actual T		reconstructed Pressure				actual Temperature			
(1953-1983) ndf = 31		stat.	period	corr.	ndf	stat.	period	corr.	ndf
*** WINTER ***									
THOM/NOTT	0.46	/NOTT	1923-1970	0.47	42	/HOPE	1891-1930	0.41	19
KUUA/MOOS	0.35	/MOOS	1932-1979	0.35	45	/HOPE	1891-1930	0.22	19
CHUR/NOTT	0.42	/NOTT	1923-1970	0.47	42	/HOPE	1891-1930	0.40	19
NOTT/NOTT	0.38	/NOTT	1923-1970	0.40	42	/HOPE	1891-1930	0.23	19
*** SPRING ***									
THOM/REDL	-.50	/REDL	1930-1979	-.38	23	/HOPE	1891-1930	-.11	19
KUUA/KUUJ	0.34	/KUUJ	1925-1979	0.28	45	/MOOF	1877-1938	0.21	43
CHUR/REDL	-.33	/REDL	1930-1979	-.09	23				
NOTT/KUUJ	0.40	/KUJJ	1925-1979	0.43	45	/MOOF	1877-1938	0.35	43
*** SUMMER ***									
THOM/MOOS	-.51	/NORW	1885-1968	-.28	38				
MOOS/NOTT	-.38	/NOTT	1923-1970	-.15	40				
KUUJ/CHUR	0.34	/YORK	1714-1870	0.27	42				
KUUA/NOTT	-.27	/NOTT	1923-1970	-.22	40	/NORW	1885-1968	0.43	38
NOTT/NOTT	0.33	/NOTT	1923-1970	0.17	40				
*** AUTUMN ***									
THOM/KUUA	-.41	/NOTT	1923-1970	-.41	42				
MOOS/NOTT	-.35	/NOTT	1923-1970	-.33	42				
KUUJ/REDL	0.50	/REDL	1930-1979	0.29	26				
KUUA/REDL	0.58	/YORK	1714-1870	0.20	42				
CHUR/KUUJ	-.39	/NOTT	1923-1970	-.28	42				
NOTT/CHUR	0.61	/YORK	1714-1870	0.51	43				

around 1840 and slightly earlier (1910-1945), in the West. Between these maxima, the winters were cold, mainly in the East. For the SLP, the important peak in 1875-1910 has no thermal correspondence. It is possible to summarize the zonality of the atmospheric circulation by the difference between the two points of extreme latitude, Moosonee and Nottingham, and its meridional character by the difference between two points of extreme longitude, Thompson and Kuujjuaq. The warm periods in the East and South-East (late 18th century and 20th century) were characterized by a weak meridional circulation. The maxima in the West were marked by a weak zonal and strong meridional circulation. The Little Ice Age, finally, has been depicted by winters with strong meridional circulation favouring polar air invasion to the South and East.

In spring (Figure 7b), the temperature seems to have the same pattern behaviour as in winter, but the amplitude of the variations is smaller. In the East, the SLP seems positively correlated with the temperature (ex. Kuujjuara-

a) winter

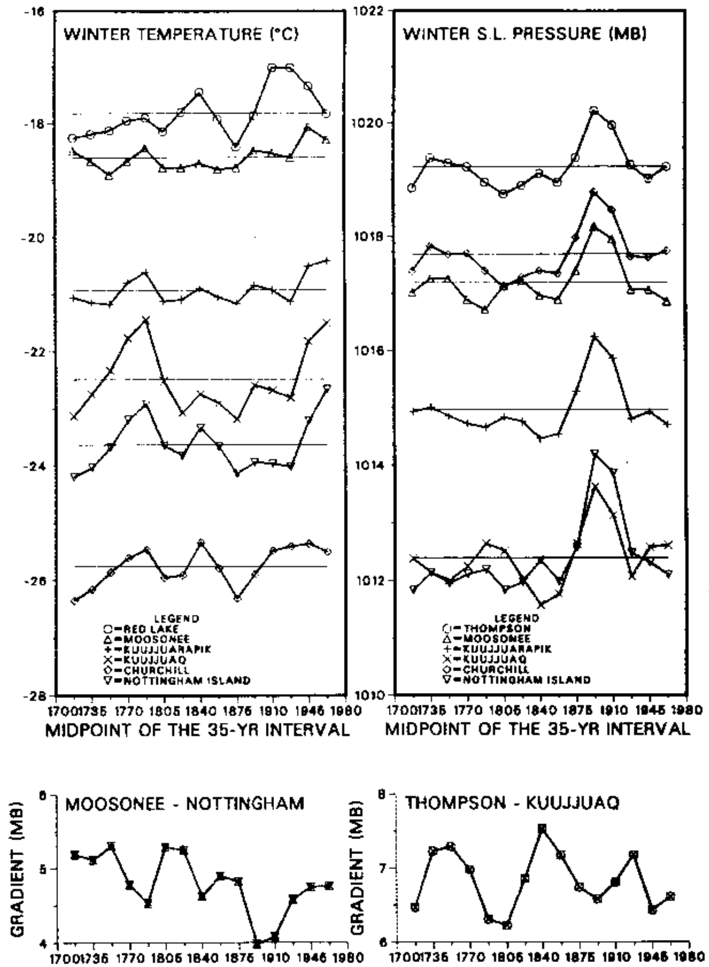
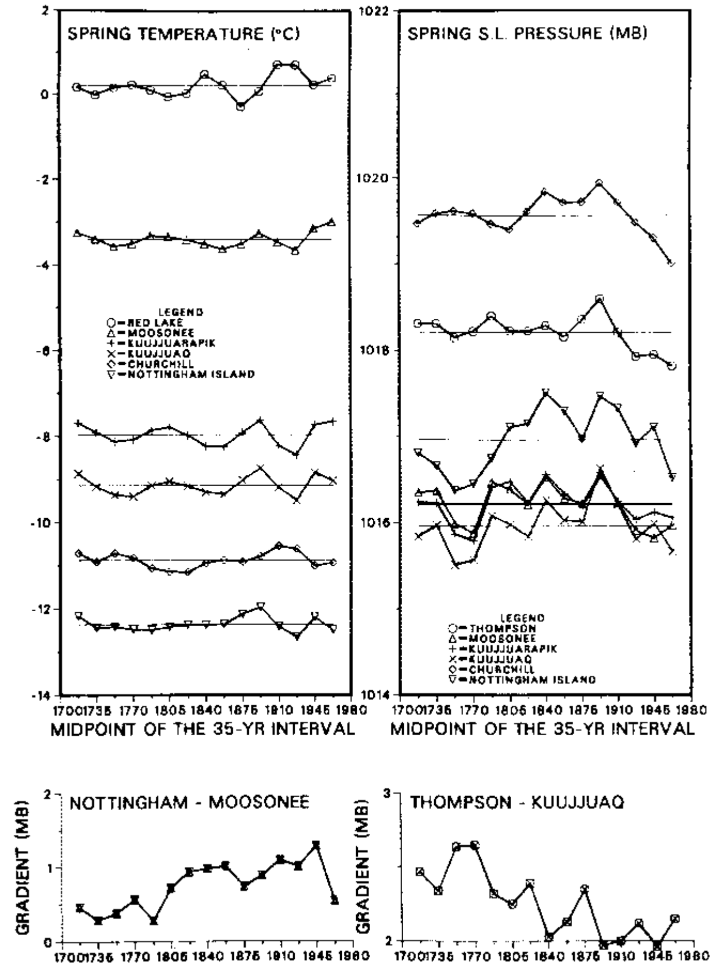
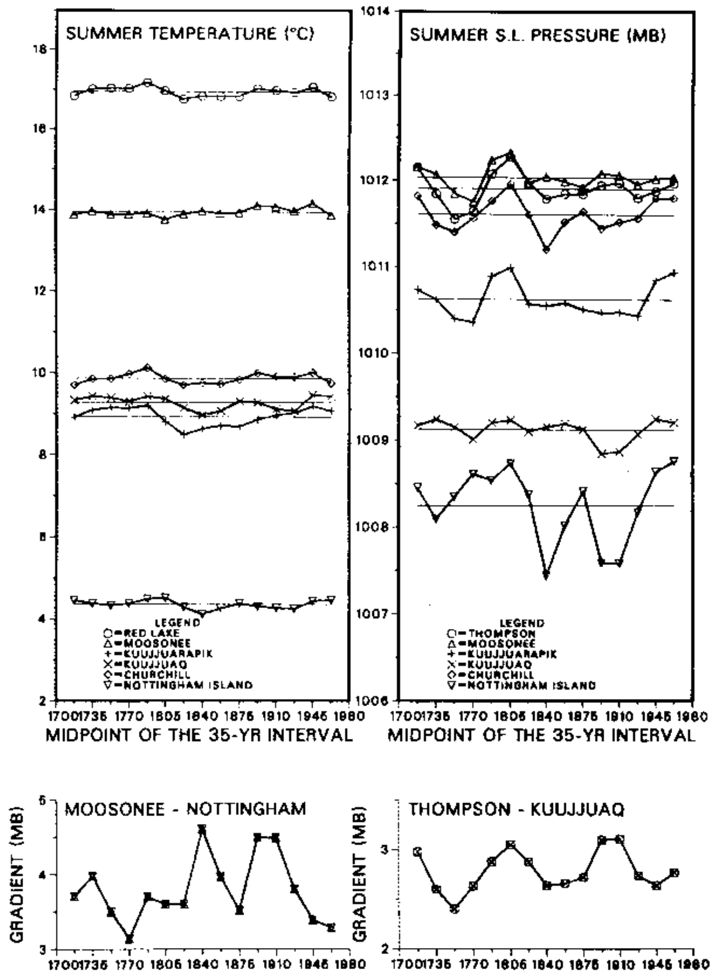


FIGURE 7. Trends of the reconstructed temperatures and SLP series: the means are computed over 35-year intervals by steps of 17.5 years. At the bottom, differences between SLP of extreme latitude (Moosonee and Nottingham Island) and extreme longitude (Thompson and Kuujjuaq) are drawn.

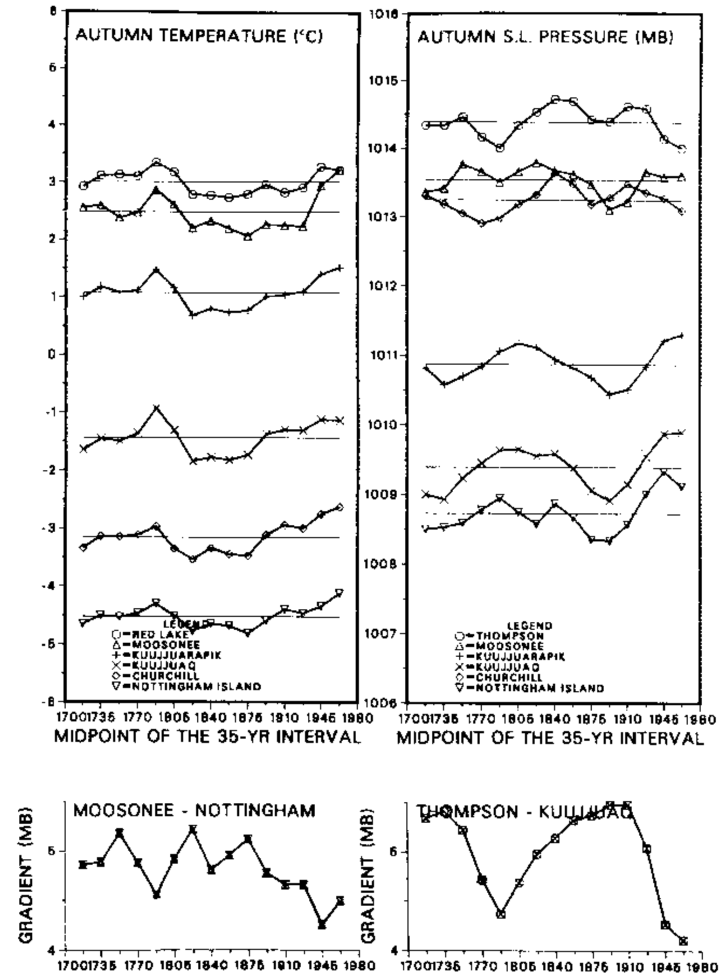
b) spring



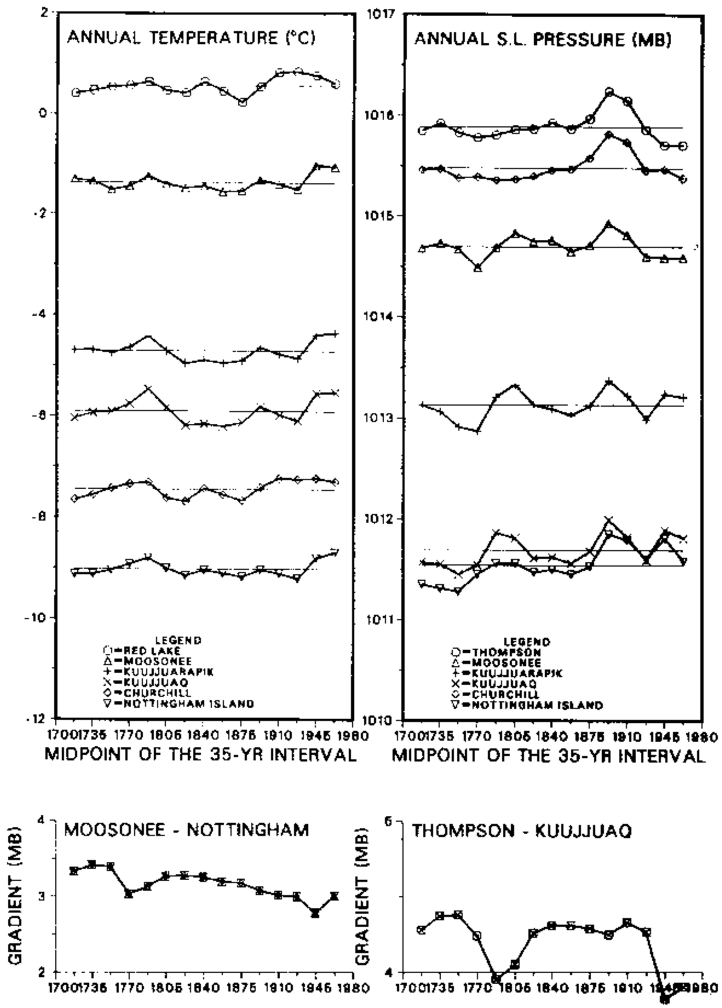
c) summer



d) autumn



e) annual



pik: minimum of SLP and T around 1735-1769 and maximum around 1875-1909). In the West, the correlations seem to be negative, since the SLP's are relatively low in the 20th century. Table 8 confirms this. The zonal and meridional circulation indices are defined at the bottom of Figure 7b. It is clear that temperature increases of the 20th century were accompanied by an increase of zonality and a decrease of the meridional circulation. The Little Ice Age was characterized by a less intense zonal spring circulation and a less dominant Atlantic low pressure regime.

In summer (Figure 7c), the temporal variations are the weakest. The SLP pattern seem to be divided between two groupings according to the means and the variations: Nottingham and Kuujjuaq located often to the North or on the trajectory of the Arctic Front and the other stations more frequently situated to the south of this front. A positive correlation seems to exist between summer temperature and SLP for the southern stations, as warm air masses more frequently invade the northern regions. For the north-eastern stations, the linkage is more complex. The SLP difference between Thompson and Kuujjuaq, summarizing the meridional character of the circulation (and thus the warm air invasion to the North), is related negatively with the temperature in the South and the West.

In autumn (Figure 7d), the maxima take place in a more synchronous way at the end of the 18th and middle 20th centuries. PC analysis has shown the relatively homogeneous character of this season. The temperatures are negatively correlated with the SLP gradient between East and West (Figure 7d, at the bottom). The Little Ice Age was marked by a strong meridional circulation in autumn.

The annual mean conditions are summarized in Figure 7e. Salient conclusions to be drawn are: (i) the Little Ice Age finished at the end of the 19th century; (ii) the annual temperature difference between the warm and cold periods (35 years) for the stations analyzed is between 0.5 and 0.9°C; (iii) low temperatures correspond generally to meridional circulation (the greatest amplitudes occur during the cold seasons, thereby influencing the annual means).

8. SYNOPTIC ANALYSIS

The 30 reconstructed temperature series are analysed by PC for the 1953-1979 interval. The first four PC's explains 86.6% of the variance. Table 9 presents the years which are linked to these PC's (positive and negative side). This indicates that eight, not necessarily independent, classes can be defined (see below).

The same analysis over 1700-1979 enables allocation of every year to one of these eight classes. The classes 1, 4, 5 and 7 are the most frequently represented during the coldest periods (before 1770 and 1805-1874) and the classes 2, 3, 6 and 8 are the most frequently represented during the 20th cen-

TABLE 9. Temperature variables influencing the most the first four PC and the years which are associated. C=cold and W=warm. The numbers of the corresponding classes are indicated in brackets.

PC	variable	years −	years +
1	annual	(1) 1972, 1978 C	(2) 1953, 1968 W
2	Summer (opposition with Winter)		(3) 1955, 1973 W
	Winter (opposition with Summer)		(4) 1956, 1969 C
3	Spring	(5) 1954, 1967 C	(6) 1977 W
4	Autumn	(7) 1959 C	(8) 1971 W

tury. This analysis describes, in a general sense, the climate of the Little Ice Age: generally cold with the possible exception in winter (mild winters are sometimes associated with cold summers). The year 1972 is the best approximation to represent this state.

Synoptic maps are presented (Figure 9) which show the geographical distribution of the climate patterns of these extreme years. Temperatures (°C) are expressed in terms of departures from the 1925-1983 mean (Figure 8) and SLP (mb) in absolute units (Figure 9). Class 1, represented by the two years 1972/1978, depicts the years with low annual temperature (−1 to −2°C). The maximum anomalies occurred in summer and autumn. Figure 8a shows maximum anomalies in the North. This class is in contrast with class 2 (1953/1968) having an anomaly of 1°C mainly around Hudson Bay and Quebec (Figure 8b). Clear differences are evident for the SLP fields between Figures 9a and 9b. A cold year corresponds to a strong pressure gradient (7 mb) with deeper cyclones located more to the North. A weak gradient (less than 3 mb) is characteristic of a warm year. Figure 8c shows that the warm autumn anomaly is important for northern Manitoba, Hudson Bay and Figure 9c shows that the high SLP extends to the West and the South, but the gradient is only 4 mb, while for a cold autumn, it can be 10 mb.

Class 3 (1955/1973) is characterized by a warm summer (1°C to 2°C) and a cold winter (0°C to −2°C). The summer anomaly is maximum in the North-West (Figure 8d) and the winter anomaly is important in the North (Figure 8e). Class 4 is the opposite to class 3 (1956/1969), with cold summers and warm winters. The winter positive anomaly is important in the East (Figure 8g) and the summer negative anomaly is important in the South-East (Figure 8f). Comparison of Figures 9d and 9f shows that high pressures climb to the North and Atlantic low pressures are deeper in a cold summer. Comparison of Figures 9e and 9g shows that warm winters are characterized by a generally higher SLP over the whole region and also be a stronger barometric gradient.

Class 5 (1954/1963/1967/1970) is characterized by a cold spring (Figure 8h) related to a northerly flux with strong highs in the West (Figure 9h). This is verified by comparison with the warm spring (Figures 8i and 9i) of class 6 (1977), when high pressure extends over the North-West and South, making a south-western flux.

The autumn of class 7 is cold (Figure 8j) mainly in the South-West. The north-eastern lows are deeper than usual (Figure 9j) and western highs are located in a more northern position. Class 8 (1971) has no particular anomaly.

In conclusion, the years 1972/1978, 1956/1969 and 1959 seem to be good models for the Little Ice Age. The temperature was cold during the whole year except during some winters which were sometimes milder in Quebec. A cold spring and autumn often prolonged the winter season mainly in the West. Zonal circulation was weak in winter and spring while the Arctic Front had a more southerly location. Other features were deeper Atlantic lows and weaker western highs.

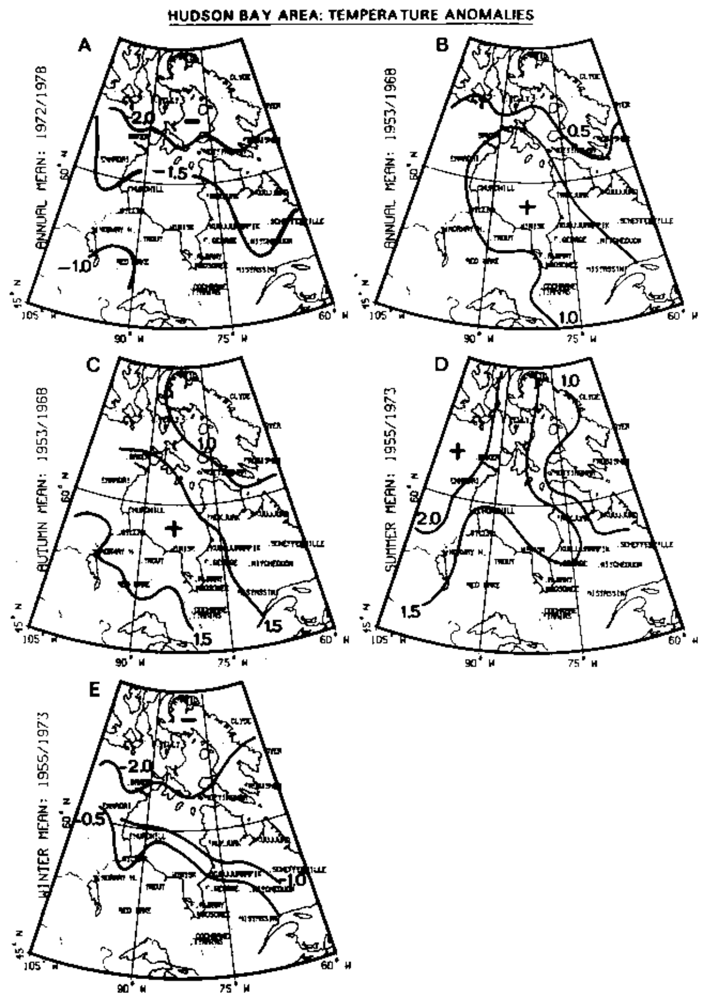
9. CONCLUSIONS

Two kinds of data have been combined to produce climatic seasonal reconstructions for a large region centered on the Hudson Bay. Historical proxy series from the Hudson's Bay Company, compiled by several authors, are well related to climate, but they are characterized by many gaps. Tree-ring data are continuous; however, their linkage with climate is sometimes complex. It has been shown that the two kinds of data are complementary. Appropriate statistical methods permit reconstructions of seasonal temperature and sea-level pressure. First, standard transfer functions show that the available proxy series network is sufficiently representative of the temperature field for the region. Thus short-term variations have been reconstructed. Second, an alternative method, based on the closest analogues, enables correction of spurious long-term variations. It seems that the analogue method alone, may be able to yield good results as well, but the series should perhaps be first "prewhitened" to reconstruct high frequencies. This hypothesis needs to be checked.

From the reconstructions, it is clear that the 18th and 19th centuries were colder than the 20th on both an annual and seasonal basis. Differences of 0.5 to 0.9°C for annual temperatures between coldest and warmest 35-year intervals are obtained. These cold periods are characterized by a less intense zonal circulation in winter and spring, and low pressures linked to a more southern trajectory of the Arctic Front in summer and autumn. Eight classes of synoptic situations have been defined, which characterize the temperatures of the 1700-1979 period. Thus the years 1972/1978, 1956/1969 and 1959 are representative of the cold periods, mainly 1805-1839, and the years 1953/1968, 1955/1973 and 1977 are representative of the warm years.

ACKNOWLEDGEMENTS

This work has been performed thanks to a post-doctoral fellowship of the Natural Science and Engineering Research Council of Canada, thanks to the



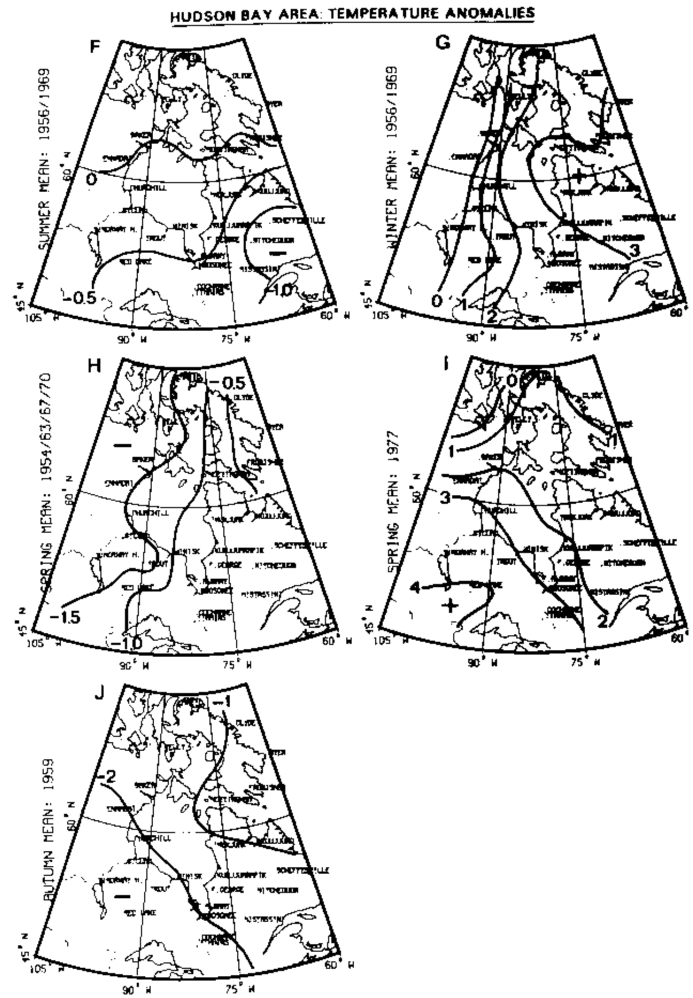
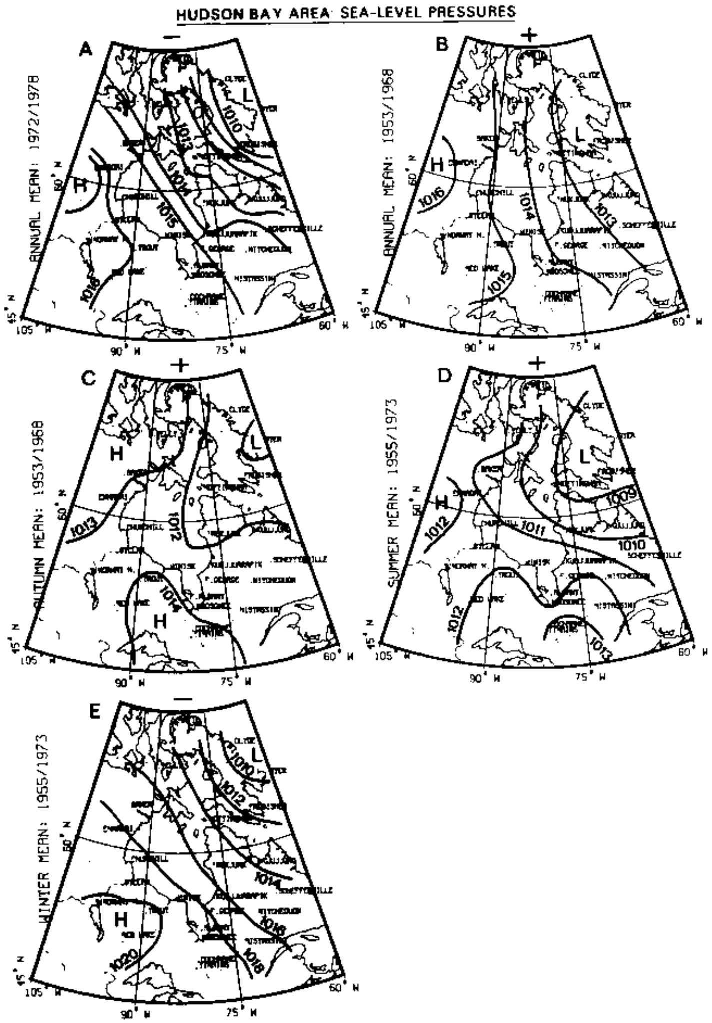


FIGURE 8. Synoptic maps of actual seasonal temperature anomalies (°C) for the years representing the eight selected classes (see text).



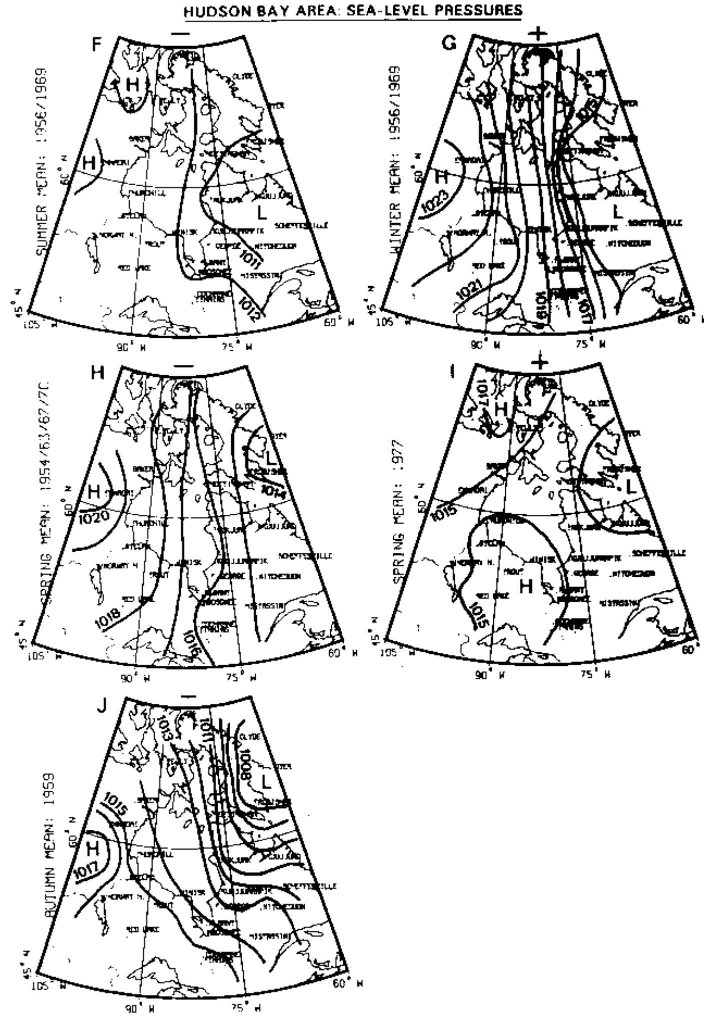


FIGURE 9. Synoptic maps of actual sea-level pressures (mb) for the years representing the eight selected classes (see text).

material support of the Atmospheric Environment Service, and thanks to the advice, comments and encouragement of Mr. B.F. Findlay. Thanks also to Mr. L. Steinberg, M. Thomas, and J. Padro for helpful comments.

BIBLIOGRAPHY

Allen, W.T.R., 1977. Freeze-up, break-up and ice thickness in Canada. Fisheries and Environment Canada, AES, CLI-1-77, 185 p.

Alt, B.T., 1983. Synoptic analogs: a technique for studying climatic change in the Canadian High Arctic. Syllogeus 49, Harington C.R., ed., Musee National des Sciences Naturelles, Ottawa, 70-107.

Ball, T., 1983. The migration of geese as an indicator of climate change in the Southern Hudson Bay region between 1715 and 1851. *Climatic Change*, 5, 83-93.

Ball, T.F., and Kingsley, R.A., 1984. Instrumental temperature records at two sites in central Canada: 1768 to 1910. *Climatic Change*, 6, 39-56.

Benzécri, J.P., et collaborateurs, 1973. L'analyse des Données (2 tomes). Dunod, Paris, 615 p, 619 p.

Blasing, T.J., 1978. Time-series and multivariate analysis in paleoclimatology. From : Time-Series and Ecological Processes. H.H. Shugart (ed.). SIAM-SIMS conference series 5, Philadelphia.

Bryson, R.A., and Hare, F.K., 1974. Climates of North America (vol 11). World Survey of Climatology, Landsberg H. (ed), Elsevier Scientific Publishing Company, Amsterdam, 350 p.

Catchpole, A.J.W., 1980. Historical evidence of climatic change in Western and Northern Canada. Syllogeus, 26, Harington (ed), Nat. Museum of Nat. Sci., Ottawa, 17-60.

Catchpole, A.J.W., and Ball, T.F., 1981. Analysis of historical evidence of climatic change in western and northern Canada. Syllogeus 33, Harington C.R. (ed), Musée National des Sciences Naturelles, Ottawa, 47-96.

Clark, D., 1975. Understanding canonical correlation analysis. University of East Anglia, Geo Abstracts Ltd, Catmog 3, Norwich, 36p.

Cropper, J.P., and Fritts, H.C., 1981. Tree-ring with the chronologies from the North America Arctic. *Arctic and Alpine Research*, 13, 245-260.

Davies, C., biologist at Queen's University, Kingston. Conversations with author at Churchill, Manitoba, August 1984, and correspondence.

Fritts, H.C., 1976. *Tree-Rings and Climate.* Academic Press, New York, 567 p.

Fritts, H.C., Blasing, T.J., Haydn, B.P., and Kutzbach, J.E., 1971. Multivariate techniques for specifying tree-growth and climate relationships and for reconstructing anomalies in paleoclimate. *Journal of Applied Meteorology*, 10, 845-864.

Guiot, J., 1985a. The extrapolation of recent climatological series with spectral canonical regression. *Journal of Climatology*, 5, 325-335.

Guiot, J., 1985b. Reconstructions des champs thermiques et barométriques de la région de la Baie d'Hudson depuis 1700. Environment Canada, SEA, Downsview, rapport interne (à paraitre, in press).

Hansell, R., (ed) 1984. Study on temporal development of Subarctic ecosystems - determination of the relationship between tree-ring increments and climate. Report to Department of Supply and Services, contract OSU84-00041.

Hillaire-Marcel, C., Occhietti, S., Marchand, L., and Rajewicz, R., 1981. Analysis of recent climatic changes in Quebec: some preliminary data. *Syllogeus* 33, Harington, C.R. (ed), Musée National des Sciences Naturelles, Ottawa, 28-47.

Hufty, A., 1982. Analyse en composantes principales de situations synoptiques du Québec. *Géographie Physique et Quaternaire*, 34, 307-314.

Imbrie, J., and Kipp, N.G., 1971. A new micropaleontological method for quantitative palaeo- climatology, application to a late Pleistocene Carribean core. *The Late Cenozoic Glacial Ages.* K. Turekian (ed), 71-181, Yale Univ. Press.

Jacoby, G.C., and Ulan, L.D., 1982. Reconstructions of past ice conditions in a Hudson Bay estuary using tree-rings. *Nature*, 298, 637-639.

Lamb, H.H., 1977. *Climate: Present, Past and Future.* Methuen, London, 825 p.

Le Roy Ladurie, E., 1967. *Histoire du Climat Depuis l'an mil.* Flammarion, Paris, 426pp.

MacKay, D.K., and Mackay, J.R., 1965. Historical records of freeze-up and break-up on the Churchill and Hayes rivers. *Geographical Bulletin*, 7, 7-16.

Moodie, D.W., and Catchpole, A.J.W., 1975. Environmental data from historical documents by content analysis: freeze-up and break-up of estuaries on Hudson Bay, 1714-1871. Manitoba Geographical Studies, 5, Univ. Manitoba, Geogr. Dept., Winnipeg.

Moodie, D.W., 1977. The Hudson Bay Company's archives, a resource for historical geography. *Canadian Geographer*, 21, 268-274.

Moodie, D.W., and Catchpole, A.J.W., 1976. Valid climatological data from historical sources by content analysis. *Science*, 193, 51-53.

Parker, M.C., Jozsa, L.A., Johnson, S.G., and Bramhall, P.A., 1981. (part 2) White spruce annual ring width and density chronologies from near Great Whale River (Cri Lake) Quebec. Syllogeus 33, Harington, C.R. (ed.) Musée National des Sciences Naturelles, Ottawa, 154-188.

Payette, S., Filion, L., Gauthier, L., and Boutin, Y., 1984. Développement d'une pessière à lichens au cours des 500 dernières années: une analyse dendroclimatique. Présenté au colloque de l'INQUA, Sherbrooke, 3 oct.

Rannie, W.F., 1983. Break-up and freeze-up of the Red River at Winnipeg, Manitoba, Canada in the 19th century and some climatic implications, *Climatic Change*, 5, 283-296.

Thomas, M.K., 1975. Recent climatic fluctuations in Canada. Environment Canada, AES, Climatological Studies 28, Toronto, 92p.

Wilson, C.V., 1982. The summer season along the east coast of Hudson Bay during the 19th century. Environment Canada, Canadian Climate Centre, Downsview, report 82-4, 223 p., + appendices.

Wilson, C.V., 1983. The little Ice Age on Eastern Hudson Bay: summers at Great Whale, Fort George, Eastmain, 1814-1821. Environment Canada, Canadian Climate Centre, Downsview, report 83-9, 145 p., + appendices.